The Project Physics Course

Supplemental Unit **A**

Elementary Particles

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Supplemental Unit A

Elementary Particles

by

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This Supplemental Unit is one of the many instructional materials developed for the Project Physics Course. These materials include Texts, Handbooks, Teacher Resource Books, Readers, Programmed Instruction booklets, Film Loops, Transparencies, 16mm films, and laboratory equipment.

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Preface

This work is intended to be used as part of a physics course or as a self-study project. One of its chief uses will be as a Supplemental Unit in classes using the Project Physics Course, a national curriculum development that grew out of the efforts of a group of scientists and educators working together as *Harvard Project Physics*.

This particular unit was developed with the resources of the publisher, Holt, Rinehart & Winston, and experimental versions of it were tried out in selected schools and colleges throughout the United States and Canada. The instructors and students in those schools reported criticisms and suggestions to the author and editors. These reports were used as the basis for the final revision. We are grateful to all who participated in these developments.

In making available a wide variety of Supplemental Units—of which this is only one, with others published, in press, or being planned—we hope to help improve teaching and studying in physics courses, whether in the Project Physics Course or in other courses, whether in colleges or schools. This is in accord with our desire to design a humanistically oriented physics course that would be useful and interesting to students with widely differing skills, backgrounds, and career plans.

In practice, this aim meant designing a course that would have the following effects:

1. To help students increase their knowledge of the physical world by focusing on ideas that characterize physics as a science at its best, rather than by concentrating on isolated bits of information.
2. To help students see physics as the wonderfully many-sided human activity that it really is. This meant presenting the subject in historical and cultural perspective, and showing that the ideas of physics have a tradition and that they also undergo evolutionary adaptation and change.
3. To increase the opportunity for each student to have immediately rewarding experiences in science even while gaining the knowledge and skill that will be useful in the long run.

4. To make it possible for instructors to adapt the course to the wide range of interests and abilities of their students.

5. To take into account the importance of the instructor in the educational process, and the vast spectrum of teaching situations that prevail.

In the years ahead, the learning materials developed by Project Physics will be revised as often as necessary in order to remove ambiguities, clarify instructions, and continue to make the material more interesting and relevant to students. We therefore urge all students and instructors to send us criticisms or suggestions, either directly to the author of this unit, or to the undersigned.

Gerald Holton
F. James Rutherford
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Co-Directors of Harvard Project Physics

Contents

Body of the 80-inch bubble chamber at Brookhaven National Laboratory being lowered onto a fixture for insertion in the stationary section of the vacuum chamber, visible at left.

Elementary Particles

PROLOGUE Elementary particle physics is one of the most exciting areas in physics today. It is a study of the most fundamental nature of matter itself, a search for the building blocks from which the physical world is made.

Particle physics is sometimes called high-energy physics, because many of its phenomena are observable only in experiments with very high individual particle energies, often 1000 MeV or more. Such high energies are needed to create the mass of most of the new particles we want to study, according to Einstein's relation $E = mc^2$. By way of comparison, a typical chemical reaction between atoms may involve 5 eV; the decay of a radioactive nucleus may involve 1 MeV; and the fission of a uranium nucleus releases 200 MeV.

1 eV = 1 electron volt, the energy acquired by a single electron in freely "falling" through a potential drop of 1 volt.
1 MeV = 1 million electron volts, and 1 GeV = 1 giga electron volt, 1000 million electron volts.
Since 1000 million is called 1 billion in the United States, the term BeV is sometimes used in place of GeV. However GeV is to be preferred because "billion" has a different meaning in Great Britain from its meaning in the United States.

The term "elementary particles" refers to those particles which cannot at this time be described as composites of other particles. Over two hundred are known today, although very few are truly stable. Most of them spontaneously decay into two or more other particles. This is a curious situation—we have particles that decay into certain products, but we cannot describe the particles simply as a combination of these products. The particles which are the most important in ordinary matter are those which do not decay by the strong nuclear force. There are 35 of these, with an average lifetime of 10^{-19} sec or more; they are listed in Table 1.1 on page 2. All the rest of the known particles are much less stable, decaying in about 10^{-23} sec. They are often called *resonances* in order to distinguish them from their more stable companions.

Some of the elementary particles—electrons, protons, and neutrons—are well-known to you from the chemistry of matter.

Positrons and neutrinos are emitted by nuclei in radioactive decay, and pi mesons, muons, and a few other particles were first observed in cosmic rays. The remaining particles on the list were not discovered until the advent of high-energy (at least 6 GeV) accelerators in the 1950's. In fact, the search for such particles has been the principal motivation for building such accelerators as the Bevatron (from BeV; see marginal note above) at the University of California at Berkeley and the AGS at Brookhaven National Laboratory.

Here we shall try to show you something of the ways of the particle physicist and to introduce you to some of the fascinating discoveries that have been made since alpha, beta, and gamma rays got their names.

TABLE 1.1 TABLE OF ELEMENTARY PARTICLES[a]

	Symbol[c]	Mass[b] (MeV)	Spin (Units of $h/2\pi$)	Parity	Baryon, Muon, or Electron Family Number	Charge (Units of $\lvert e \rvert$)	Strangeness	Lifetime (seconds)
Photon Family								
Photon	γ	0	1	—		0	0	Stable
Electron Family								
Electron	e^-	0.5	$\frac{1}{2}$		+1	−1	0	Stable
Positron	e^+	0.5	$\frac{1}{2}$		−1	+1	0	Stable
Electron's neutrino	ν_e	0	$\frac{1}{2}$		+1	0	0	Stable
Electron's antineutrino	$\bar{\nu}_e$	0	$\frac{1}{2}$		−1	0	0	Stable
Muon Family								
Mu minus	u^-	106	$\frac{1}{2}$		+1	−1	0	2.2×10^{-6}
Mu plus	u^+	106	$\frac{1}{2}$		−1	+1	0	2.2×10^{-6}
Muon's neutrino	ν_μ	0	$\frac{1}{2}$		+1	0	0	Stable
Muon's antineutrino	$\bar{\nu}_\mu$	0	$\frac{1}{2}$		−1	0	0	Stable
Meson Family								
Pi zero	π^0	135	0	—		0	0	0.8×10^{-16}
Pi plus	π^+	140	0	—		+1	0	2.6×10^{-8}
Pi minus	π^-	140	0	—		−1	0	2.6×10^{-8}
Kay plus	K^+	494	0	—		+1	+1	1.2×10^{-8}
Kay minus	K^-	494	0	—		−1	−1	1.2×10^{-8}
Kay zero	K^0	498	0	—		0	+1	0.9×10^{-10} [d]
Antikay zero	$\bar{K}^0$	498	0	—		0	−1	5.4×10^{-8} [d]
Eta	η^0	549	0	—		0	0	2×10^{-19}

[a] Adapted from Particle Data Group, Physics Letters, August 1970. This list includes only particles with a lifetime of at least 10^{-19} sec.

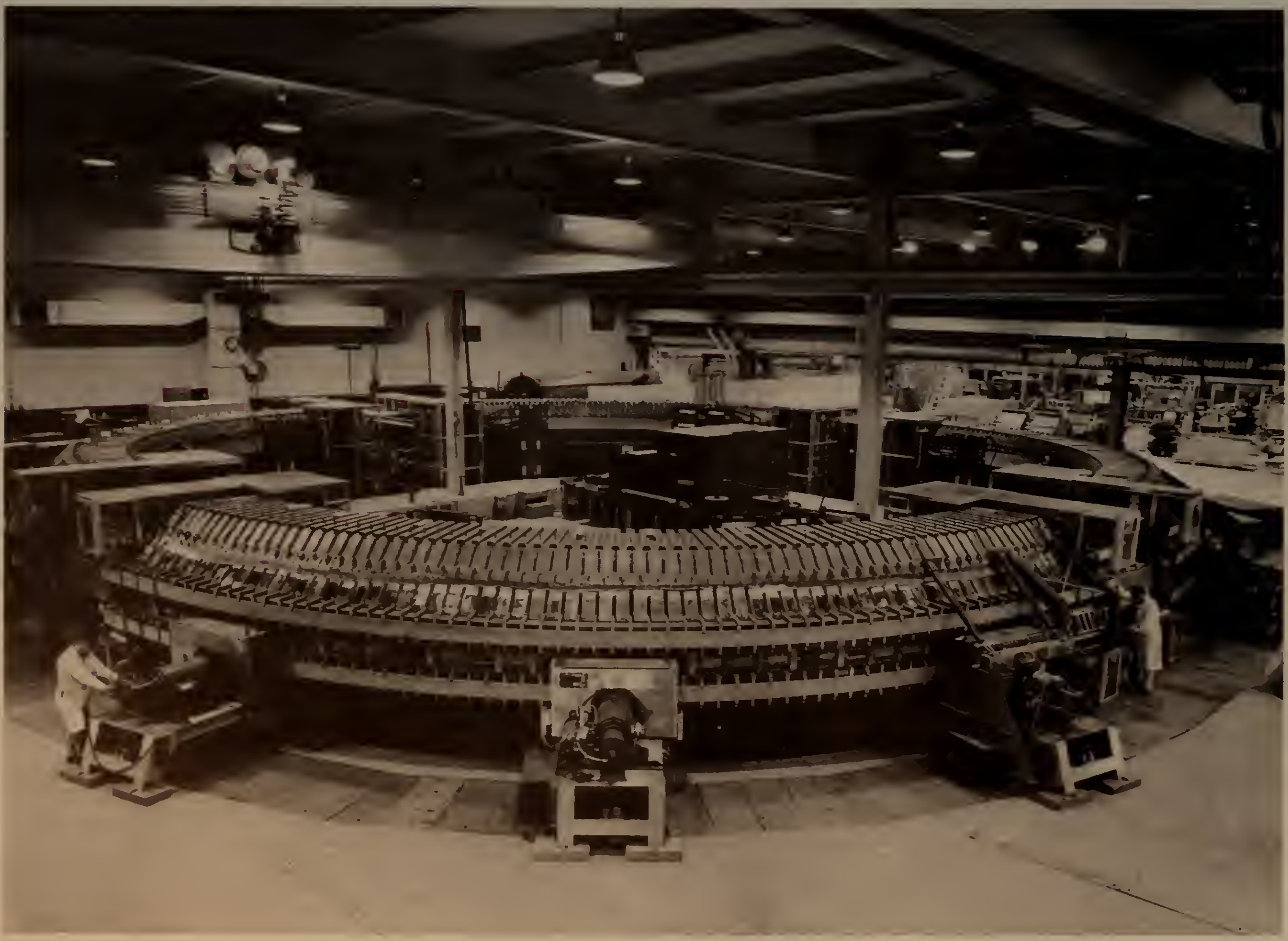
[b] The "mass" quoted is actually the value of mc^2 in MeV, i.e. the rest energy.

[c] The bar over a symbol indicates an "antiparticle", which is the same as the corresponding "particle" except for having opposite family number, charge, and strangeness.

[d] A beam of K^0 or $\bar{K}^0$ mesons shows two different lifetimes: half the particles decay with the short lifetime and half with the longer one.

[e] Observed for the first time at U. of California, Berkeley, December 1970.

	Symbol[c]	Mass[b] (MeV)	Spin (Units of $h/2\pi$)	Parity	Baryon, Muon, or Electron Family Number	Charge (Units of $\|e\|$)	Strangeness	Lifetime (seconds)
Baryon Family								
Proton	P^+	938	$\frac{1}{2}$	+	+1	+1	0	Stable
Antiproton	$\bar{P}^-$	938	$\frac{1}{2}$	+	−1	−1	0	Stable
Neutron	N^0	940	$\frac{1}{2}$	+	+1	0	0	10^3
Antineutron	$\bar{N}^0$	940	$\frac{1}{2}$	+	−1	0	−0	10^3
Lambda	λ^0	1116	$\frac{1}{2}$	+	+1	0	−1	2.5×10^{-10}
Antilambda	$\bar{\lambda}^0$	1116	$\frac{1}{2}$	+	−1	0	+1	2.5×10^{-10}
Sigma plus	Σ^+	1189	$\frac{1}{2}$	+	+1	+1	−1	0.8×10^{-10}
Antisigma, minus	$\bar{\Sigma}^-$	1189	$\frac{1}{2}$	+	−1	−1	+1	0.8×10^{-10}
Sigma zero	Σ^0	1192	$\frac{1}{2}$	+	+1	00	−1	$<10^{-14}$
Antisigma, zero	$\bar{\Sigma}^0$	1192	$\frac{1}{2}$	+	−1	0	+1	$<10^{-14}$
Sigma minus	Σ^-	1197	$\frac{1}{2}$	+	+1	−1	−1	1.5×10^{-10}
Antisigma, plus	$\bar{\Sigma}^+$	1197	$\frac{1}{2}$	+	−1	+1	+1	1.5×10^{-10}
Xi zero	Ξ^0	1315	$\frac{1}{2}$	+	+1	0	−2	3×10^{-10}
Antixi zero	$\bar{\Xi}^0$	1315	$\frac{1}{2}$	+	−1	0	+2	3×10^{-10}
Xi minus	Ξ^-	1321	$\frac{1}{2}$	+	+1	−1	−2	1.7×10^{-10}
Antixi, plus	$\bar{\Xi}^+$	1321	$\frac{1}{2}$	+	−1	+1	+2	1.7×10^{-10}
Omega minus	Ω^-	1673	$\frac{1}{2}$	+	+1	−1	−3	1.3×10^{-10}
Antiomega, plus[e]	$\bar{\Omega}^+$	1673	$\frac{1}{2}$	+	−1	+1	+3	1.3×10^{-10}



The Cosmotron at Brookhaven National Laboratory.

CHAPTER ONE

Some Basic Concepts and Experimental Methods

In this first chapter we introduce the basic ideas of particle physics as well as the major experimental techniques used in this field. Our purpose is to provide a useful background for the more detailed study that lies ahead.

1.1 Families of Particles

Table 1.1 lists the 35 most stable elementary particles. You can see that these particles have been grouped into families: the photon, the electron family, the muon family, the mesons, and the baryons. The family to which a particle belongs is important because it is determined by some of the particle's basic properties: its *interactions* and its *spin*. These properties will be explained in Sections 1.2 and 1.3.

The baryon family includes all particles which participate in the strong interaction (Section 1.2) and which have odd half-integer spin ($\frac{1}{2}$, $\frac{3}{2}$ --- etc.). The muon and electron families include all particles which do not participate in the strong interaction and which have odd half-integer spin.

The meson family includes all particles which participate in the strong interaction which have integer spin (0, 1, --- etc.). The photon is the only particle that has yet been observed which has integer spin but does not participate in the strong interaction, so it is in a family by itself.

Two of the family names were originally derived from the Greek: barys means heavy, and baryon is the name given to particles at least as heavy as the proton, while meso means middle, and the name meson applies to particles intermediate in mass between the proton and the muon. Each of the other families is named for one of its important members.

As more has been learned about elementary particles, some changes have had to be made in the way they are classified. For example, certain recently discovered particles are heavier than protons but behave in other respects like the mesons, so these are called mesons despite their mass. Also, the muon was originally considered one of the mesons, but on further observation it was found to behave differently from the other members of that family and was assigned to a family of its own.

1.2 Forces Between Particles

Forces can do many things: they can bind particles together to form a stable compound system, they can cause one particle to "bounce off" another in a scattering experiment, and they can cause an unstable particle to decay into two or more different particles. However, as far as we know, there are only four fundamental types of force in the world, and the only way in which one particle can influence another is by means of one of these forces, or interactions as they are often called. Two of the basic forces are old friends: the *gravitational* and *electromagnetic* forces. Another, the *strong force*, is the shortrange force that holds nuclei together, as discussed in Unit 6, Section 24.7. The fourth force, the *weak force*, is probably new to you. Not all particles experience all of these forces. Particles in the photon, electron, or muon families do not participate in the strong interaction. Photons do not participate in the weak interaction, while mesons do so, but only in an indirect way. Otherwise, all particles can produce and be acted upon by any of these four basic forces. To understand the elementary particles, it is essential to understand these forces.

We shall introduce these four interactions briefly, in order of increasing strength. As a measure of their relative strengths, we will use the average time it would take for an elementary particle to decay into lighter products by means of each force. The stronger the force, the shorter the time.

The *gravitational interaction* is very important in our everyday world, but that is only because ordinary objects contain huge numbers of elementary particles. Actually, the gravitational force among individual particles is so weak that it is completely unobservable in the reactions of particle physics. It would take a particle something like 10^{48} years (10^{55} sec) to decay due to the gravitational interaction.

The *weak interaction* is responsible for beta decay, the process by which radioactive nuclei emit electrons, as well as for the decay of many elementary particles. When the decay of a particle is due to the weak interaction, it takes about 10^{-10} sec.

The *electromagnetic interaction*, of which the Coulomb (electric) force is an example, binds electrons to positive nuclei to form atoms and molecules, and binds molecules together to form solids. This interaction is also responsible for the emission of light from excited atoms as they "decay" from their excited state to their normal or "ground" state. In elementary particle physics, an electromagnetic decay may take 10^{-16} sec or so.

The *strong interaction* is the force that holds a nucleus together in spite of the electrical repulsion among its protons. Because of its strength its effects are dominant whenever it is present. The most unstable particles that we know of are called resonances, and they decay by means of the strong interaction in the very short average time of 10^{-23} sec. At first it may seem rather strange that the same forces which cause two particles to be bound together in one situation will cause an unstable system to decay in another situation. To indicate how this comes about we must make a short digression and introduce a little field theory, using as an example the electromagnetic force.

You are familiar with the notion that charged particles produce an electromagnetic field and that such a field produces forces on other charged particles. Thus a hydrogen atom containing internal charges can produce an electromagnetic field, and this field can attract another hydrogen atom. The two atoms can be bound together into a hydrogen molecule by electromagnetic forces.

On the other hand, if that same hydrogen atom is produced in an excited energy state it can undergo electromagnetic decay by emitting light and dropping to its ground state. In this case the hydrogen atom produces an electromagnetic field (the light) which becomes completely detached from the atom and then propagates away. Thus we have the decay of an unstable "particle," the excited hydrogen atom, due to electromagnetic forces

$$\begin{pmatrix}\text{H atom in}\\ \text{excited state}\end{pmatrix} \rightarrow \begin{pmatrix}\text{H atom in}\\ \text{ground state}\end{pmatrix} + \begin{pmatrix}\text{electromagnetic}\\ \text{radiation}\end{pmatrix}$$

The situation is similar for the other interactions mentioned above, although the weak interaction is too weak to cause observable bound states. The mechanism by which these basic forces act is discussed further in Section 3.6 of this unit.

Curiously, bound states are readily observed for the weakest interaction of all, the gravitational interaction. However, these are not states involving just two elementary particles, but rather they are states involving huge aggregates of particles, such as the earth itself. The range of the weak interaction is too short for it to be significant in a similar way in the interaction of macroscopic bodies.

1.3 Properties of Particles

Elementary particles are usually identified by the familiar properties of *mass* and *charge*. It is customary to express the mass of elementary particles in MeV, although the quantity actually given in

these units is really the energy equivalent to the mass according to the usual relation $E = mc^2$. The charge of a particle is its electric charge, and the unit of charge is the magnitude of the charge of an electron. Particles usually have a charge of 0, +1, or −1, although particles with charges of +2 and −2 have also been found.

$h = 6.63 \times 10^{-34}$ J sec or kg m^2/sec

Baryon family number is usually shortened to just *baryon number.*

Particles also may have *spin,* internal angular momentum similar to that which the earth has due to its rotation about its own axis. Although particles are surely not little rotating spheres, each particle has a particular unchanging value of spin, characteristic of that kind of particle. You may recall that in the hydrogen atom angular momentum is quantized, coming only in integer multiples of a fundamental unit equal to $h/2\pi$, where h is Planck's constant. It turns out that particles may have spin equal to an integer, a half-integer, or zero in these units.

Each of the particles with odd half-integer spin has the special property that one product of any reaction in which it participates is always a particle belonging to the same family as the original particle. Physicists have found it useful to speak of any particle with this property as having a *family number* corresponding to the family to which it belongs. Its other family numbers are considered to be zero. Only particles in the electron family have a non-zero *electron family number,* only particles in the muon family have a non-zero *muon family number,* and only particles in the baryon family have a non-zero *baryon family number.* Photons and mesons do not have any family numbers. The physicist describes the special property noted above by saying that family numbers are *conserved* in all physical reactions. The significance of conservation of family number is discussed in Section 2.4 and 3.7.

The *lifetime* of an unstable particle is completely analogous to the lifetime of a radioactive nucleus. It is simply the average time a particle of a given type exists before it decays.

Strangeness is a new property that will be discussed in detail in Sections 2.6 and 4.2.

Parity is another internal property, which for our purposes is just one more identifying characteristic of an elementary particle. It has to do with the relation between the matter wave representing a particle and the mirror image of that wave. If $f(x)$ is the function representing the original wave, and $f(-x)$ is the function representing the mirror image wave, $f(-x) = f(x)$ if the parity is positive but $f(-x) = -f(x)$ if the parity is negative. Particles may have either positive or negative parity.

To give a general idea of what it means, we will describe parity in a classical situation: the vibration of a violin string. The simplest

kinds of standing waves that are possible have either positive or negative parity, as shown in Fig. 1.1. If the parity is positive the standing wave and its mirror image are identical, but if the parity is negative, the mirror image goes up where the original wave goes down, and vice versa. Thus positive parity applies to symmetric waves, while negative parity applies to antisymmetric waves.

Parity has been much more important in the development of physics than we can show here, as it led to some of the most interesting developments of the last decade. If you wish to look further into this matter, the article by Martin Gardner, "The Fall of Parity," in the Reader for Unit 6 is a good one.

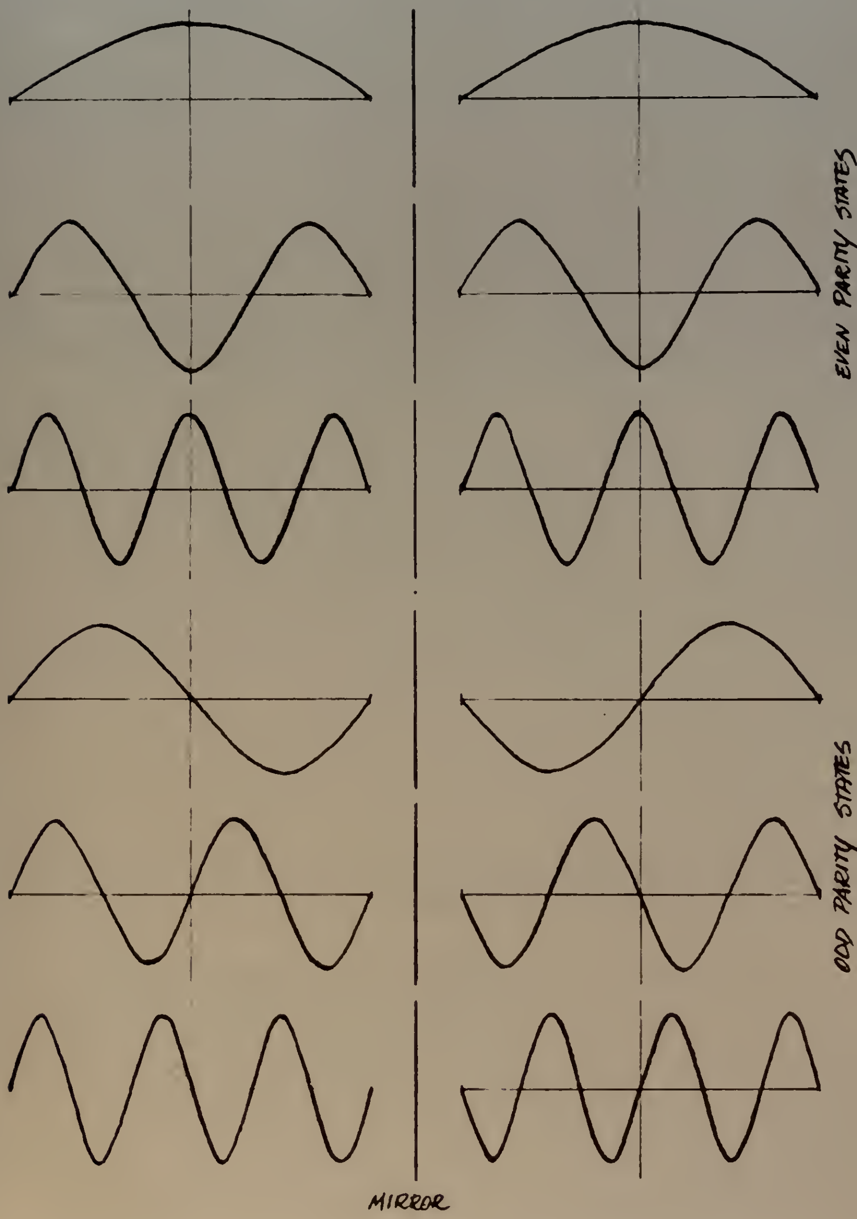


Fig. 1.1 Waves on a violin string. For positive parity waves the wave and its mirror image are identical. Negative parity waves have a mirror image with positive and negative displacements interchanged.

1.4 Conservation Laws

Perhaps the most important laws in the physical world, and certainly the most important in particle physics, are the *conservation laws*. Almost everything we will do in this book will be based upon one or several conservation laws. A physical quantity is said to be conserved if its value for a closed system cannot change, despite any internal changes in the system, as long as there is no outside influence. For example, in a reaction involving charged particles, the final particles may be quite different from the original ones, but the total charge of all the products must be the same as the total charge of all the particles that entered into the reaction.

Thus for a conserved quantity, if we total the values for all the particles in a closed system before any reaction, and then add them up again after the reaction, we will find this total unchanged. There are seven such quantities known: four refer only to internal properties of the particles themselves, while the other three have to do with their external motion as well. Thus there are seven conservation laws which are absolute: they hold without known exception. There are other "conservation laws" used in physics, but they are not absolute, since they only hold part of the time. They will not be included here. The following quantities are those that are always conserved:

1. Charge
2. Baryon number
3. Muon family number
4. Electron family number
5. Energy
6. Momentum
7. Angular momentum

1.5 Accelerators

We now turn to the experimental side of things and discuss some of the equipment used in particle physics.

In order to get the high energies needed in particle physics, experiments are usually carried out at one of the great accelerator facilities (such as the ZGS in Illinois—see Fig. 1.2), although some work is still done with cosmic rays. Accelerators are very convenient because they provide intense beams of particles which can readily be chosen and controlled by the experimenter. Their only major limitation is the maximum energy of the machine, and accelerators have been built to bring particles up to energies as high as 33 GeV.

Fig. 1.2 Aerial view of the Zero Gradient Synchrotron (ZGS) at Argonne National Laboratory, Illinois.

The synchrotron itself is housed in a ring-shaped building approximately 30 feet square in cross section and 200 feet in diameter. In the center of this "doughnut" there is another building, the Center Building. This contains four floors of equipment and a control room in the fifth (top) floor. The Ring Building is covered by a mound of earth with a minimum thickness of 20 feet. The linear accelerator is housed in a building about 120 feet long, also covered by a mound of earth. A roadway running up the side and around the top provides access to the center building. The experimental buildings are adjacent to the machine.

Cosmic rays provide a "beam" of particles coming from outside the earth, although this "beam" has the disadvantages that it is not under the control of the experimenter and that it is much lower in intensity than the beams produced by an accelerator. However, cosmic ray experiments do have one great advantage for certain purposes: a few cosmic ray particles have energies far above those available at any accelerator.

Since the cost of a large accelerator is in the tens or even the hundreds of millions of dollars, as the energy and size of the machines go up the number available gets smaller. Thus scientists from all over the world gather at the highest-energy facilities to do their experiments. Table 1.2 on the next page lists the major installations. They are broken up into two groups, depending on whether they accelerate protons or electrons. There are some design differences between machines in the two groups, but for our purposes

the important difference is in the kind of particles they produce. Electron accelerators are usually used as sources of electron or photon beams, while proton accelerators are used to produce beams of protons, mesons, or antiprotons, among others.

TABLE 1.2 MAJOR ACCELERATOR FACILITIES FOR PARTICLE PHYSICS

Proton Accelerators

Date of Completion	*Name and Location*	*Energy (GeV)*
1952 (recently retired)	Cosmotron, Brookhaven National Laboratory, Long Island, New York, U.S.A.	3
1954	Bevatron, Lawrence Radiation Laboratory, Berkeley, California, U.S.A.	6.2
1960	Proton Synchrotron (PS), European Organization for Nuclear Research (CERN), Geneva, Switzerland	28
1961	Alternating Gradient Synchrotron, (AGS), Brookhaven, Long Island, New York, U.S.A.	33
1963	Nimrod, Rutherford Laboratory, Harwell, England	7
1963	Zero Gradient Synchrotron (ZGS), Argonne National Laboratory, Illinois, U.S.A.	12.5
1967	Synchrotron, Serpukhov, U.S.S.R.	70
1972	Synchrotron, Batavia, Illinois, U.S.A. (under construction)	500
1975	Synchrotron, European Collaboration (CERN II) Geneva, Switzerland (Planned)	300

Electron Accelerators

Date of Completion	*Name and Location*	*Energy (GeV)*
1960	Mark III, Stanford University, Stanford, California, U.S.A.	1
1961	Linear Accelerator, Orsay, France	2
1962	Cambridge Electron Accelerator (CEA), Cambridge, Massachusetts, U.S.A.	6
1964	Deutsches Electronen synchrotron (DESY), Hamburg, Germany	6
1966	Stanford Two-mile Linear Accelerator (SLAC), Stanford, California, U.S.A.	20
1967	Electron Synchrotron, Yerevan, Armenia, U.S.S.R.	6

Let us discuss the operation of the ZGS as an example of a typical proton accelerator. Although electron accelerators are similar in principle, many of them are built in a linear rather than a circular configuration. Basically, the ZGS consists of a long evacuated tube, bent into the shape of a ring 200 feet in diameter. The proton beam travels in the tube, held in a circular orbit by a magnetic field provided by eight large magnets placed around the circumference of the ring. On each trip around, the protons pass through three accelerating cavities with a voltage drop of 20,000 volts across each, so that a proton gains 60,000 electron volts of energy each time around the ring. Of course, as the proton velocity increases, the magnetic field is also increased in order to hold the beam in the same circle.

The protons are obtained by ionizing hydrogen gas in an electrical discharge, much like that in a neon sign. Then they are accelerated to 50 MeV in a linear accelerator ("linac"), consisting of 124 electric accelerating cavities in a line. About every 4 seconds an "inflector" magnet is pulsed in order to guide a bunch of protons from the end of the linac through a thin metal window into the main ring, where they stay for about 200,000 revolutions, until they reach full energy. This takes about 0.2 seconds, during which they travel 30,000 miles—farther than the distance around the world! At this time there are over 10^{12} protons, each with an energy of 12.5 GeV, in the circulating beam inside the accelerator.

1.6 Beams of Particles

Once the protons or electrons reach their highest energy inside an accelerator, they may be released into the experimental area associated with the accelerator, as a beam pulse for use in an experiment. If a beam with a different kind of particle is desired, it is produced as a secondary beam. To do this, a strip of metal called a target is quickly flipped into the path of the beam in the accelerator, and numerous particles of many different kinds are produced in the resulting nuclear collisions. Then the desired kind of particle, with the desired energy, must be selected from among all the others that have been produced in the target. This selection is accomplished by using magnets and electrostatic separators (Fig. 1.3 on the next page) in much the same way that prisms and lenses are used to select a beam of light of a particular wavelength from the complete spectrum radiated by a light bulb. The extracted primary beam or secondary beam is then carried in vacuum pipes to the experimental area. What strikes the final target is a short stream of particles uniform in mass, energy, and type.

This leads to the question of how the particles are used experimentally once a beam has been obtained. The typical experiment consists of studying the collision or "scattering" that

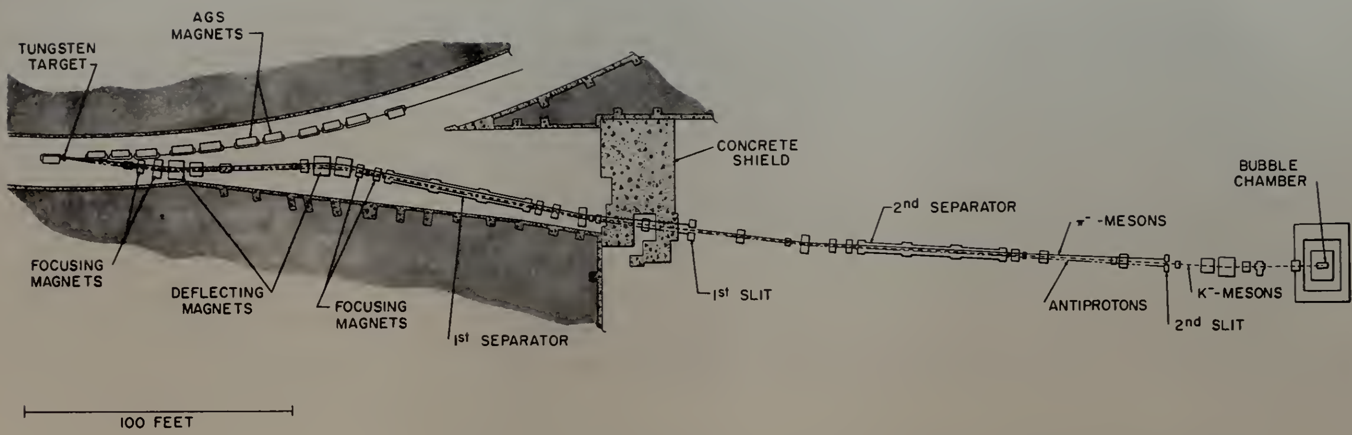


Fig. 1.3 A secondary beam of 5-GeV K^- mesons is produced at a proton accelerator. After acceleration, the internal proton beam hits a tungsten target (left). Focusing magnets gather secondary particles from the target; deflecting magnets send particles of the desired momentum to the electrostatic separator; the separator deflects particles according to their mass and focuses the desired particles on a slit (1 × 0.05 inch) that blocks most of the undesired particles. This process is repeated at a second separator and slit. Before separation the ratio of K^- mesons to π^- mesons to antiprotons is 10 to 800 to 10. As the beam enters the bubble chamber, after two stages of separation, the ratio has been improved to 10 to 1 to 0.

This is quite similar to the scattering of alpha particles by atomic nuclei (Rutherford scattering) which you studied in Unit 6, although in that case neither the incident nor the target particle was an elementary particle in our sense of the word.

takes place when a beam particle A hits a target particle B. In equation form, this may be written

$$A + B \rightarrow ?$$

There are many possibilities in this situation, including the possibility of getting entirely new particles out of the reaction. The target particle is usually a proton or a neutron, and these are conveniently available in ordinary matter. The beam particles are chosen as desired by the experimeter from among those that are not too rare and that can live long enough to travel through the apparatus without decaying. Some of the reaction products may have low velocities even with a high-energy incident beam.

1.7 Detection Devices

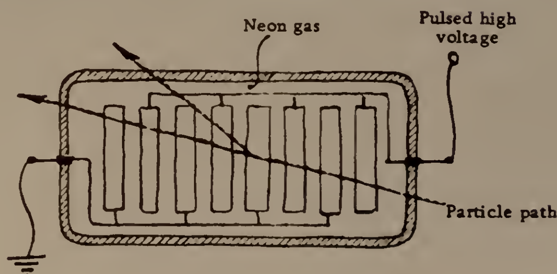
There are several ways to observe the final particles produced in a scattering experiment. Instruments such as Geiger counters and scintillation counters are frequently used, either alone or in connection with other kinds of detectors. There are also several kinds of visual devices that can record in detail the tracks made by the particles being studied. The first of these visual detectors was the Wilson cloud chamber, which has been in use since 1912. At present most work is done with a bubble chamber or a spark chamber. All three devices rely on the fact that fast charged

Fig. 1.4 Spark chamber picture of particle tracks. The long straight track is that of a muon created by an incident neutrino. Another track is also seen entering from the left. This is probably a gamma ray.

particles can produce ions by knocking electrons out of atoms. Thus, in passing through any of these chambers, each particle leaves a trail of ions along its path. The next step is to form by some means a visible track along the ion trail and to photograph this track to obtain a permanent record of the particle's path.

A spark chamber is a tank filled with a gas such as neon and containing a stack of metal plates with insulating spacers between them. A high voltage can be applied between adjacent plates so that the passage of a charged particle will cause sparks to jump along the ion trails left in each gap (Fig. 1.4). Counters are placed around the chamber, and set so that they will apply the high voltage and photograph the chamber only when a desired sequence of events takes place. For example, the counters could be set to

Fig. 1.5 Spark Chamber (schematic).



trigger the chamber if and only if one particle enters and two particles leave the chamber within a very short time interval. The greatest advantage of spark chambers over bubble chambers and cloud chambers is this ability to be triggered only when there is evidence that something interesting has happened. Its greatest disadvantage is that the line of sparks left along the track of a particle is rather wide and allows only moderate precision in the measurement of the direction and curvature of the track. Fig. 1.4 is a photograph of an event in a spark chamber.

Since bubble chamber photographs will be used extensively in our discussions, the next sections describe the bubble chamber in somewhat greater detail.

1.8 Bubble Chambers

The bubble chamber was invented in 1952 by Donald A. Glaser at the University of Michigan, allegedly from an idea he conceived while contemplating bubbles forming in a glass of beer. In the case of beer (no pun intended) the formation of bubbles is uncontrolled, but it is possible to create another situation where bubbles appear only at desired locations.

Basically, a bubble chamber is just a tank containing a superheated liquid—that is, a liquid which is on the verge of boiling, but which has not quite begun to boil. The question then arises as to where the boiling will first begin. Where will the first bubbles be formed? Ordinarily, they will be formed near some nonuniformity like a sharp edge on the wall of the tank or a speck of dirt in the liquid. One such nonuniformity could be an ionized atom. We have noted that when a fast charged particle passes through a device such as a bubble chamber, a trail of ions is produced right along the track of the particle through the chamber. These ions are the seeds around which bubbles grow when the liquid just starts to boil. If we can photograph this trail of bubbles before the bubbles drift away from the place where they were formed (say within a thousandth of a second after the beam passes through the chamber), we will have a record of the exact trajectory of every charged particle traveling in the chamber.

The amount of ionization decreases with increasing particle speed down to some minimum ionization. This is because a fast particle has less time to act on a given atom than a slower one does. Thus a track with low bubble density implies a high-velocity particle, while a dense track is left by a low-velocity particle.

After a beam pulse has passed through the chamber and the results have been photographed, it is necessary to remove all bubbles and restore the liquid to its superheated condition. This is done by first applying pressure to the liquid until all the bubbles are compressed out, and then, just as the next beam pulse is about to arrive in the chamber, releasing the pressure to make the liquid become superheated again. Typically, this entire cycle can be completed in a large bubble chamber once every second.

Fig. 1.6 Tracks in a bubble chamber.

Many liquids are suitable for the formation of bubbles, but there is an additional consideration involved in choosing a liquid: the chamber liquid provides the target particles in the interactions which are to be studied. Ordinary hydrogen is the preferred bubble chamber liquid; the hydrogen nucleus consists of a single proton, so that if a nuclear collision occurs the experimenter knows that a beam particle must have interacted with a proton. Hydrogen is also convenient because collisions between two bodies are mathematically much simpler to study than those involving more particles. Sometimes, however, an experiment calls for neutrons as the target particles, in which case it is most convenient to fill the chamber with deuterium (heavy hydrogen), the simplest substance that contains neutrons. Since the deuterium nucleus contains a proton as well as a neutron, it is necessary to make corrections for the presence of the proton.

A superheated liquid is not necessarily hot—its temperature is just the boiling point of that particular substance at the prevailing pressure. At a pressure of 30 pounds per square inch, hydrogen is superheated at −412°F.

Fig. 1.7 Neutrons can be detected indirectly, as in this photograph, which shows a large number of short proton tracks left by protons recoiling from collisions with incoming neutrons. An intense neutron beam was traveling from left to right.

Special "heavy liquids" like xenon are often used in a bubble chamber when the experiment is concerned with the behavior of neutral particles. Neutral particles do not leave tracks in any bubble chamber, but they can enter into secondary reactions with identifiable charged products (Fig. 1.7). The probability of such secondary reactions is greatly increased by the presence of heavy nuclei such as carbon, which are found in these special liquids. However, even in hydrogen, it is often possible to observe the tracks of protons scattered by the impact of neutral particles and thus to gain information about the neutral particles themselves.

The use of liquid hydrogen immediately complicates the building of a bubble chamber, because the boiling point of hydrogen is 412° below zero, Fahrenheit. Therefore, if hydrogen is used, the entire bubble chamber must be placed inside a sophisticated type of refrigerator.

In order to get complete three-dimensional information about the tracks left by particles in the chamber, it is necessary to take several photographs at once of each track from different angles. Human beings are able to obtain three-dimensional information such as distance by a sort of mental triangulation made possible by the fact that our two eyes allow us to view the same object from two slightly different angles at once. To do the same thing in the bubble chamber would take at least two views. We, however, have the further advantage that we can move or turn our heads to place our eyes in the best possible position for seeing a given event. To make up for the fact that the cameras used with a bubble chamber are fixed in position, it is customary to use three instead of only two.

The connection between momentum and curvature is discussed in more detail in Section L3 of "Laboratory Experiments in Particle Physics" at the end of this unit.

Still more information about the events taking place in a bubble chamber can be obtained if the chamber is placed in a strong uniform magnetic field. This field causes all charged particles to move in curved paths, with the amount of curvature dependent on their momentum and the direction of curvature dependent on their charge. By making measurements on photographs of the tracks, physicists can determine the charge and momentum of every particle of interest. The quality of such photographs must be so high that these determinations can be made quite accurately, and a bubble chamber with a magnetic field becomes, among other things, a precision momentum-measuring machine.

1.9 The Brookhaven 80-inch Bubble Chamber

To give some idea what a large bubble chamber is really like, we include here the specifications and some pictures (Figs. 1.8-1.11) (Also frontispiece) of the 80-inch chamber at Brookhaven National Laboratory. It should be obvious from these that such a chamber is built, and remains, in the location where it is to be used, near a large accelerator.

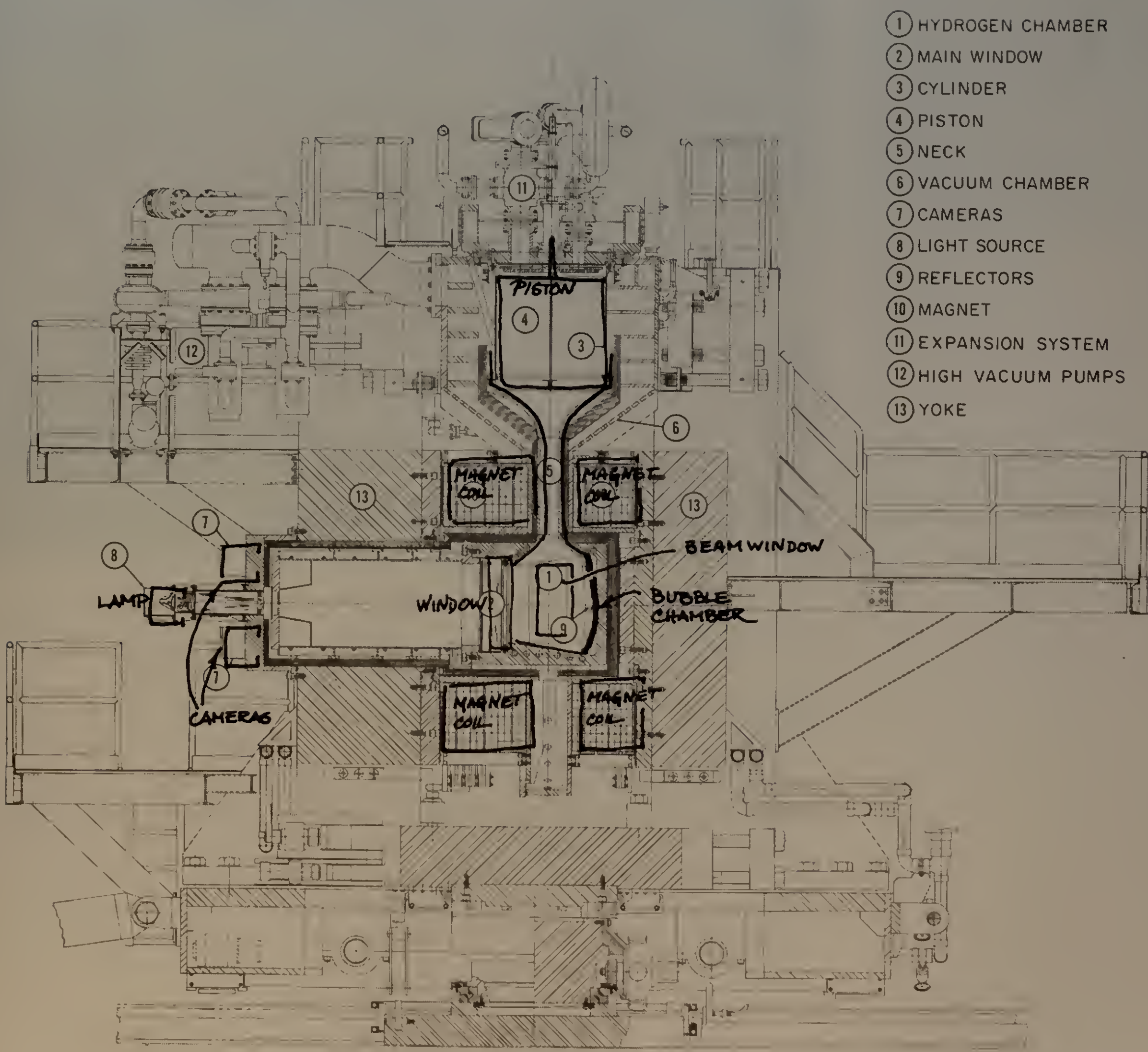


Fig. 1.8 Schematic cross section of the 80-inch liquid hydrogen bubble chamber showing major components.

Fig. 1.9 The 80-inch bubble chamber assembly. At the left side of the chamber, on the first gallery, is the aperture through which illumination is provided and photographic equipment installed. Below the gallery, to the left, can be seen part of the hydraulic ram that moves the chamber assembly into position as required by the experimental program. In the chamber, liquid hydrogen is superheated by a sudden reduction in pressure, timed to coincide with the entrance of pulsed particles from the Brookhaven accelerator. Tracks of the particles are photographed by means of a camera and light source synchronized with the formation of bubbles along the ion trails. The curvature of the tracks in a magnetic field indicates the mass, electric charge, momentum, and other properties of the particles.

SPECIFICATIONS OF THE 80-INCH BUBBLE CHAMBER

Liquid	Hydrogen or deuterium
Volume	400 gallons
Dimensions	seen by cameras: 80 × 27 × 26 inches
Weight	chamber, magnet, carriage, vacuum tank: 480 tons
Pressure:	80 pounds per square inch
Cycling rate	One expansion per second
Window	Glass, optical quality,: 81 × 30 × 6½ inches thick
Cameras	Three or four, 70-mm film, 1000-foot rolls
Refrigerator	Compressor power: 500 horsepower
Magnet	Field: 2.04 weber per square meter
	Power: 4 megawatts (16,000 amps at 250 volts)
	Cooling water: 570 gallons per minute
	Copper weight: 31 tons
Sponsor	United States Atomic Energy Commission
Cost	$6 million, including buildings and facilities
Date	Ready for physics experiments October 1963

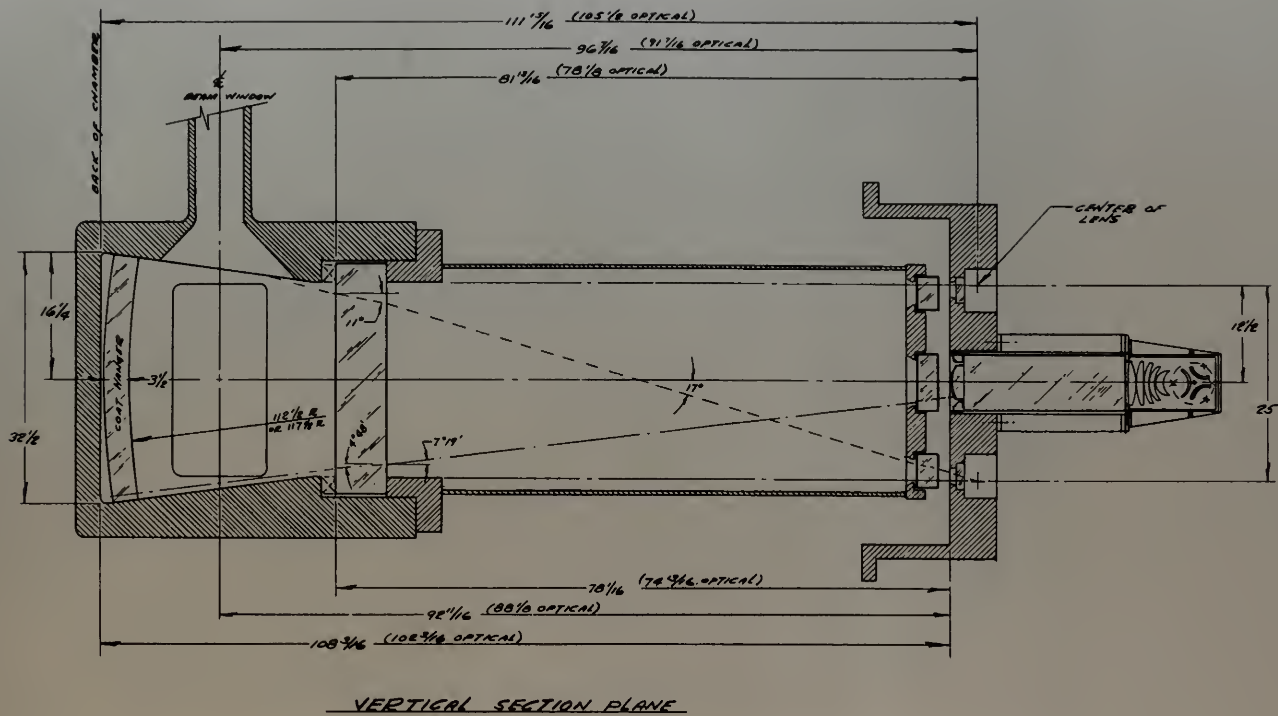


Fig. 1.10 Schematic of the arrangement used to photograph the tracks. The light-source assembly (right), consisting of a xenon-filled quartz tube and an optical condenser system, focuses the light into the bubble chamber. The light then travels toward the back of the chamber (left), where it is reflected back toward the source. Some of the light is scattered by the bubbles toward the camera windows, where an image of the bubble can then be produced.

1.10 How Bubble Chamber Photographs are Used

Once the photographs are taken, the long process of analysis begins. Unlike the spark chamber, the bubble chamber produces photographs for every beam pulse, whether the desired events have occurred in the chamber or not. Thus the first step is scanning—looking at the film to find those pictures that do contain events of the type to be studied. Once these pictures are found, it is necessary to get detailed information from them about the location, direction, and curvature of each track. Precise measurements are made of the locations of several points along each track of interest. One way this can be done is with a measuring machine, which displays the picture on a screen together with a movable cross hair. The cross hair can be moved to any desired point on the picture and the location of that point punched automatically on an IBM card when the operator presses a foot pedal. The data for a complete event, now on IBM cards, is taken to a large digital computer, where it is run through a program that analyzes it in detail.

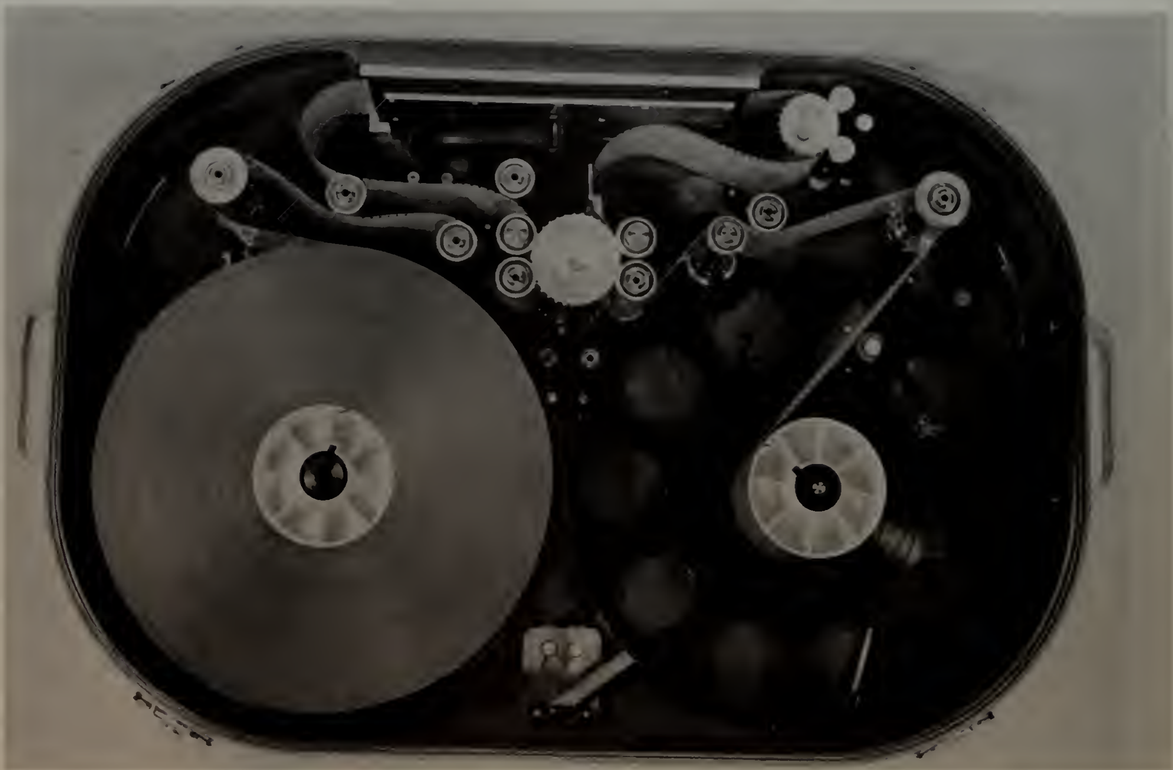


Fig. 1.11 Loaded camera magazine. Film from the spool at the left is guided through mechanical drives past the opening at the top, where it is exposed to the bubble images provided by a photographic lens. The mechanism must advance ≈ 6 inches of 70-mm film every second. The film must be very flat in order to avoid distortion; it is therefore pulled back against a metal plate by a vacuum.

Fig. 1.12 Operator measuring tracks in a measuring machine.

Many events of a given type must be collected and analyzed in this way before the physicist can come to a specific result, such as "The mass (or rest energy) of the Σ^+ (sigma plus) particle is 1189 MeV."

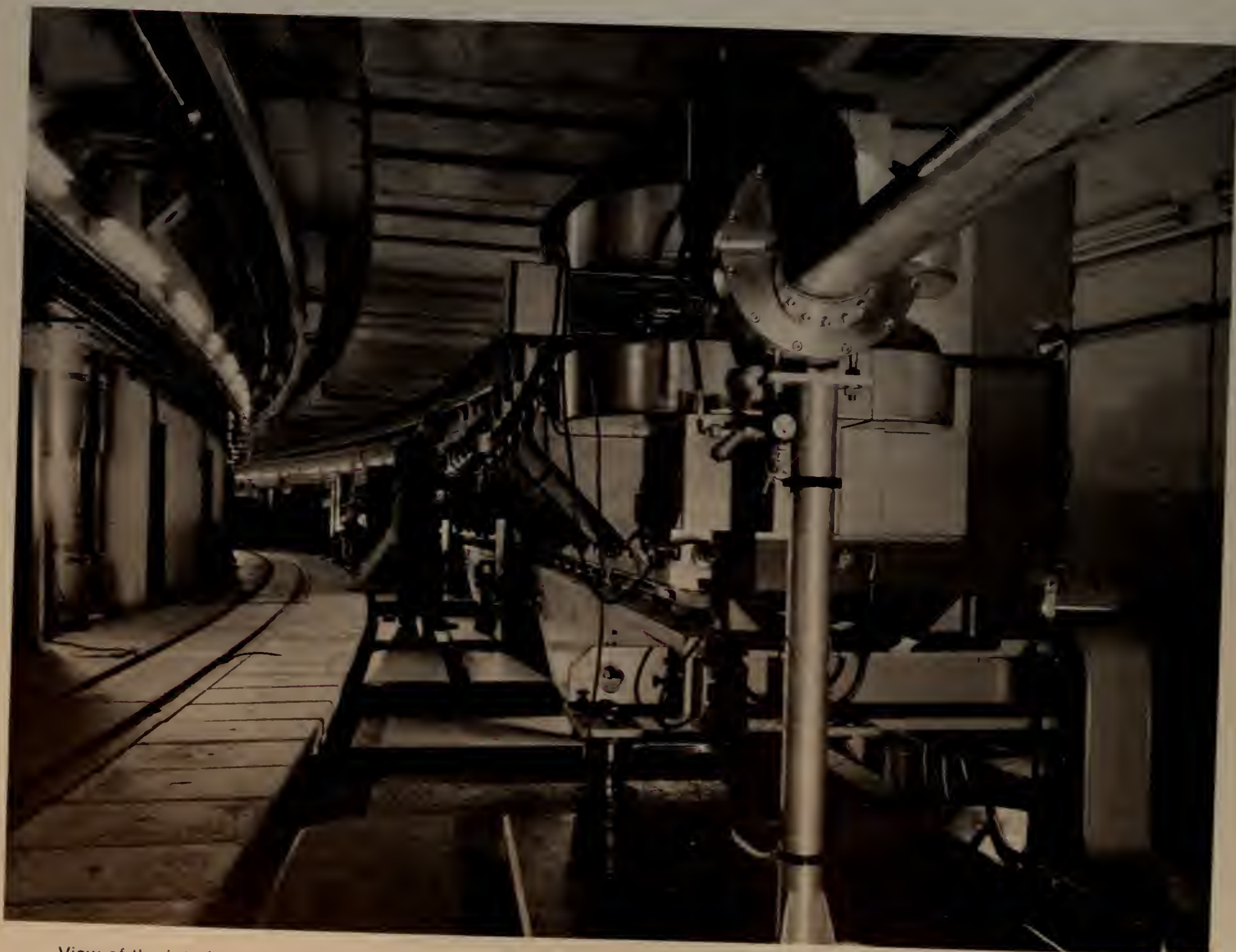
Much effort is currently going into the development of systems that can gather data automatically from the film and send it directly to the computer without any direct human intervention. It is expected that this will speed up the process of analysis and allow us to perform larger experiments as well as to search for much rarer events than we have been able to so far. Around 1963, a group of 20 PhD's, 15 graduate students, and 80 technicians analyzed 100,000 events per year. This constituted about four or five physics experiments. They used 12 scanning projectors, 4 measuring machines, and 40 hours per week of computer time to do this, and the total cost was well over a million dollars a year. Surely any efficiency that can be introduced by automated methods will be more than welcome.

Q1 Consider the particles listed in Table 1.1 and group them according to their charge. Which group has the greatest number of particles? Are there as many positive as negative particles?

Q2 There are seven absolute conservation laws listed in Section 1.4. State each of these laws in your own words, making clear what it is that is conserved.

Q3 For one of the major accelerators listed in Table 1.2, look up the specifications, including energy, ring diameter, number of revolutions, beam intensity, injection accelerator, etc. The public information office at the accelerator can be quite helpful if you want more information than you can find in your local library.

Q4 In Section 1.8 it is stated that at least two cameras are required in order to record three dimensional information in a bubble chamber. Draw a light-ray diagram showing how this would work.



View of the interior of the CERN 28 GeV proton synchrotron.

CHAPTER TWO

A Guided Tour Through the World of Particles

2.1 Introduction

We are about to depart on a tour in which we will see elementary particles in action as they move in a liquid hydrogen bubble chamber. Some of these are beam particles; others are the products of collisions between beam particles and particles at rest in the chamber; still others are products of decay. The pictures recording their motion are actual-size prints of the "left eye" views from stereo pairs taken at the 10-inch chamber at the Lawrence Radiation Laboratory of the University of California at Berkeley. This chamber was used several years ago in connection with Berkeley's 6.2-GeV accelerator to perform various physics experiments involving the events you will see here and many more like them.

Because the stereo camera in this chamber uses a lens spacing equal to that of human eyes, the pictures are also well suited for stereoscopic viewing. A "Viewmaster" slide wheel with complete stereo pairs for each event is available for those who would like to see how the tracks really look in three dimensions. Although the two-dimensional prints selected for this book are quite adequate for discussion of the physics, the three-dimensional pictures are so striking that every effort should be made to see them. The three-dimensional pictures also contain information about the motion of the particles toward or away from the camera that is not available from the two-dimensional print, although our discussion will not require that information. The prints we will use are negatives, showing the tracks as dark lines against a light background, although in actuality the tracks in the bubble chamber appear bright against a dark background.

The 3-D "Viewmaster" slide wheel may be available in your class. If not, it can be obtained from The Ealing Corporation, 2225 Massachusetts Avenue, Cambridge, Mass. Viewers are of a type that is generally available, but Ealing offers them as well. A self-lighted viewer is recommended.

The chamber has a magnetic field of 1.2 weber per square meter in a direction parallel to the camera axis—that is, perpendicular to the plane of the pictures. This allows us to find the component of the momentum vector in the plane of the picture for any particle.

The weber per square meter is the mks unit of field. 1 web/m^2 = 10,000 gauss.

We make this calculation from the radius of curvature of the particle's track, using the relation

$$p_1 = 3.6\ r \text{ (for 10-inch chamber)}$$

where p_1 is the momentum component in the plane of the picture in MeV/c and r is the radius in cm. This relation is obtained by substituting the actual value of the field in the general relation derived in Section L3 at the end of this unit for the motion of a charged particle in a magnetic field. The total momentum p can be obtained from p_1 by simple trigonometry once the angle between the track and the plane of the picture is established by a three-dimensional reconstruction of the track. In the special case where the track is parallel to the plane of the picture, p equals p_1 and this added step is unnecessary. This will generally be the case for any pictures selected here that use momentum measurements.

2.2 An Electron Spiral

Figure 2.1 shows a large spiraling electron track in a bubble chamber. Electron tracks are easily recognizable, because no other particle can make a track which has such a low bubble density combined with such a small radius of curvature. Furthermore, with the chambers and magnetic fields presently available, no other particle can make a complete circle in a bubble chamber: if it is slow enough it stops before making a complete circle, and if it is not slow enough to stop it goes on through the chamber before it can make a circle.

Electrons are characterized by a high range (length of path) in relation to their momentum. A graph of range versus momentum (Fig. L3) is included with Experiment 2 at the end of this unit. Once we have calculated initial momentum and range for the particle in Fig. 2.1, we can see clearly from the graph that only an electron could have such a high range for such a low initial momentum.

This chapter is semi-programmed. Many paragraphs such as this one end with a question which should be answered by the reader before going on. An answer is generally given in the following paragraph which should not be consulted until the reader has formulated his own answer.

1. Study the large spiraling electron track in Fig. 2.1. Recall that the radius of curvature of a track measured in the plane perpendicular to the magnetic field is proportional to the momentum of the particle that made the track. Using the fact that the particle loses energy and momentum to the hydrogen along its path, can you tell whether the electron spirals in toward the center, or out from the center?

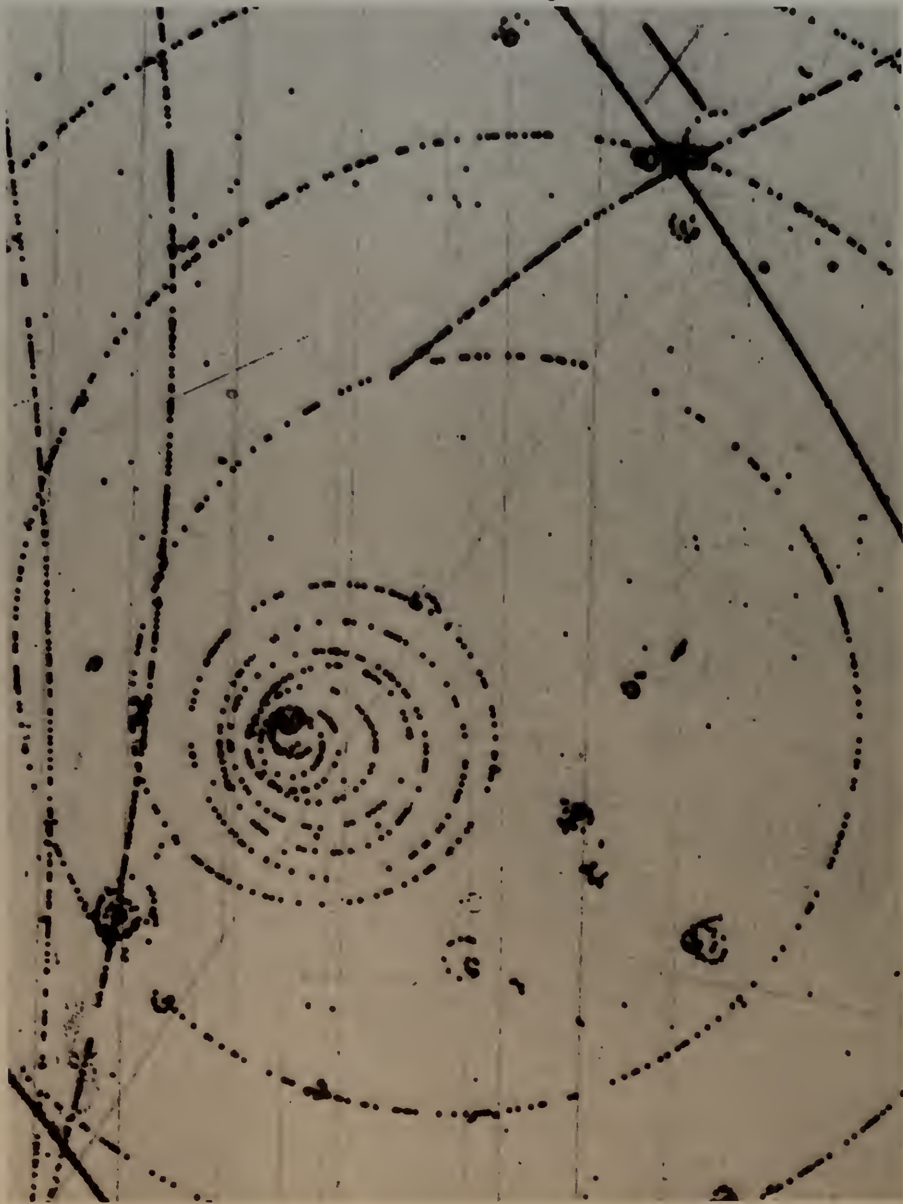
2. The electron spirals in, as do the other electrons that made the smaller spirals in the picture.

Fig. 2.1 An electron spiral (actual size).

Once you know the direction of travel of the particle along its track, you can determine its charge. The magnet of the bubble chamber is so oriented that the magnetic field direction is perpendicular to the plane of the picture, toward the reader looking at the page. In order to produce a circular path, the magnetic force on the particle must be towards the center of the circle. As we discuss in Section L3, the direction of the magnetic force on a positively charged particle is connected with the field and the velocity by a right-hand rule, while the force on a negatively charged particle would be in the opposite direction. What is the sign of the charge of this particle?

Although this path is not exactly circular, it is near enough to allow us to treat any small section of it as if it were a circle, to a good approximation.

Fig. 2.2 Electron spiral taken in another bubble chamber (about half size). Some tracks of other particles also appear.



3. This particle has a negative charge, as do all particles that spiral counterclockwise in this magnetic field. Later on we will encounter some particles that travel clockwise in the same field; these will be positive particles.

This electron had rather high energy when it originated outside the chamber. The smaller spirals come from relatively low-energy electrons, generally knocked out of the hydrogen atoms in some sort of collision process. Since there are very many electrons in the hydrogen of a bubble chamber, such collisions are quite likely, and most pictures you see will have several small electron spirals in them. Incidentally, almost all tracks with this general appearance

are made by negative electrons (single positive electrons are relatively rare), so that you can use electron spirals to determine the direction of the magnetic field if that is not given.

Using this technique, find the field direction in Fig. 2.2, which is a photograph of an electron spiral from another bubble chamber.

4. By applying the right-hand rule, and taking into account the negative charge of the electron, we find that the field direction is again out of the page.

Next, some quantitative measurements can be made on the track in Fig. 2.1. In order to present the physics here with clarity, avoiding the complexity of analyzing a track in three dimensions, we have chosen a photograph in which the plane of the electron track is so close to that of the photograph (that is, the angle of dip between the planes is so small) that for practical purposes the electron track can be assumed to lie in the plane of the photograph. In the case where a track does lie in the plane of the picture, the momentum of the particle is perpendicular to the magnetic field, so that p and $p_\perp$ are equal.

As mentioned at the beginning of this chapter, the photographs we are studying are actual size. It is therefore possible to measure the radius of the particle track and then calculate the initial momentum of the particle according to the equation $p(\mathrm{MeV/c}) = 3.6r$ (cm), presented in Section 2.1. Using a centimeter scale, you can measure from the center of the spiral to the point where the electron appears to have entered the chamber and thus get the initial radius of curvature of this track. How much is the initial momentum of the electron?

5. The initial momentum is about 28.1 MeV/c. However, by measuring at later points in the spiral, you can see that the momentum continuously decreases. What value does the momentum reach in the last visible turn?

6. In the last turn, the momentum has dropped to, at the most, 0.7 MeV/c. Although the electron continued to slow down and eventually stops, measurements on the very end of the track are difficult because the radius of curvature is small and changing very rapidly.

Notice, however, that the last portion of the track is nearly as dotted as the first part, which suggests that the velocity of the electron is still fairly high near the end. (The faster the particle travels, the fewer atoms it ionizes.) To calculate the velocity from the momentum, the correct relativistic expression is:

$$v = c\,\frac{pc}{\sqrt{(m_0c^2)^2 + (pc)^2}}$$

As discussed in Section 1.2, the basic equations of relativistic mechanics are:

$$E = mc^2 = \sqrt{(m_0c^2)^2 + (pc)^2}$$

$$p = mv = mc^2\,\frac{v}{c^2}$$

Therefore $p = \dfrac{v}{c^2}\sqrt{(m_0c^2)^2 + (pc)^2}$

and $v = c\,\dfrac{pc}{\sqrt{(m_0c^2)^2 + (pc)^2}}$

Q.E.D.

Physicists often use the word "velocity" to mean the magnitude of the velocity vector. Whether the velocity vector or just its magnitude is meant should be clear from the context, so we will use "velocity" in both ways in this unit.

Using this relation, we find that the velocity of the electron varies from 3×10^8 m/sec down to 2.5×10^8 m/sec, so that it is nearly equal to the velocity of light for the entire observed part of the path. This explains the uniformly dotted appearance of the track. However, it leaves us with the question of how the momentum of the particle could have changed so greatly when its velocity remained nearly constant. Can you explain this?

7. The change in the electron's momentum was due almost entirely to a change in its mass. At relativistic speeds, momentum p = mv. However, m is not the rest mass, but the relativistic mass, which increases with velocity. Thus $m = p/v$ and $mc^2 = \frac{pc}{v/c}$. Since $v \simeq$ c everywhere down to the last turn of the spiral, $mc^2 \simeq pc$, and we have already shown that pc varies from 28.1 MeV down to about 0.7 MeV so the relativistic mass varies between these same limits. This contrasts with the rest mass of the electron, which is only about 0.5 MeV!

It is also of some interest to compute the time it took the electron to make the complete path that you see. The path length can be measured by winding a string along the spiral and then measuring its length, or by measuring the diameter of each turn of the spiral and assuming that the circumference of a turn is about the same as the circumference of a circle with the same diameter. How long is the path length, as found by measurement on the picture?

8. The total path length is about 100 cm. A look at the range versus momentum graph accompanying Experiment 2 for a particle which could combine a range of 100 cm with an initial momentum of 28 MeV/c confirms that the particle we are studying is indeed an electron. At an average velocity of about 2.7×10^{10} cm/sec, the electron took only 3.7×10^{-9} sec to travel its 100 cm. To us this seems a very short time, but on the time scale of elementary particles it is rather long. Look how far this electron can go in such a time, or compare this time with the mean lifetimes of most of the unstable particles in the Table of Particles.

2.3 Multiple Proton Scattering

1. In Fig. 2.3 we see many tracks; in order to make any sense out of this photograph, we must concentrate on a single track or set of connected tracks at one time.

The chamber is arranged as before, with the magnetic field out of the page and the incident beam entering the chamber at the bottom of the picture. You will see nearly a dozen tracks entering together at the bottom and passing on through the chamber. These

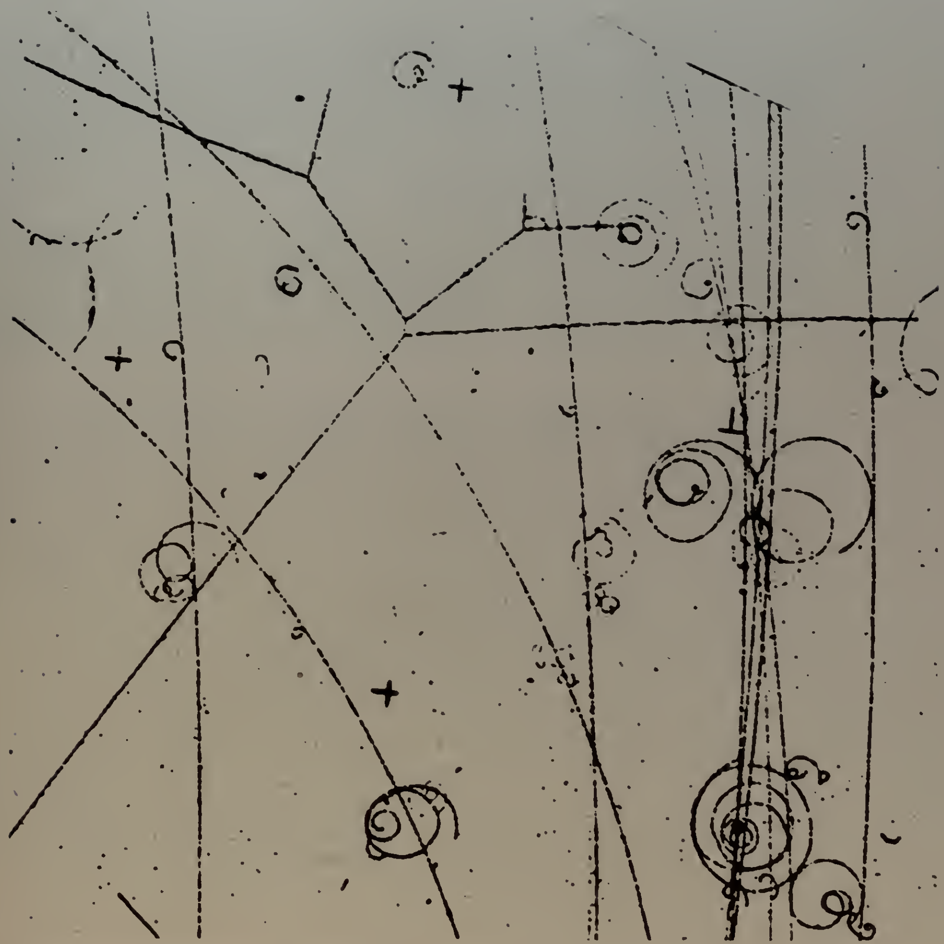


Fig. 2.3 Multiple proton collisions (actual size).

If you look at this picture on the 3-D slide wheel, turn the viewmaster upside down to make the directions identical.

are beam tracks. Can you determine the sign of the charge of the beam particles from the direction of curvature of their tracks?

2. Since the tracks curve counterclockwise they are made by negative particles.

Notice the small spirals scattered around throughout the picture. What do you think made them? Is their direction consistent with your assumption?

3. They are electron spirals, and the counterclockwise curvature is consistent with the negative charge carried by an electron.

The beam tracks are much straighter than the electron tracks, that is they have a much larger radius of curvature. What does this imply about the relative momenta of the beam particles and the electrons?

4. The straighter the track, the higher the momentum of the particle that made it, so the momentum of the beam particles is clearly much higher than that of the electrons. In fact, measurements on the picture show that the beam particles have about one hundred times the momentum of a typical electron. Do you know how you could determine this ratio?

5. We have seen above that the radius of curvature of a track is directly proportional to the momentum of the particle that made it. Thus the momenta of two particles are in the ratio of the radii of curvature of their tracks.

There is an interesting set of connected tracks in this picture; these are sketched in the margin and numbered for identification. At first glance it would seem impossible to tell which tracks are incoming and which are outgoing in this event, especially since none of them seems to be a beam track. However, we do not expect to see a pair of particles that originated at separate points coming together at a vertex with only one track coming out. Thus, for example, of tracks 1, 2, and 9, only one is likely to be an incoming track. The incident particle hits something at point V and then both the target and incident particles make tracks leaving point V. Furthermore, we can make an intelligent guess as to which is the incoming track. If this event is connected in any way with the beam, its particles are much more likely to travel in the same general direction as the beam than in the opposite direction. This suggests that track 1 may be the incoming track. Although it is clearly not a beam particle itself, particle 1 may have been produced in a collision of a beam particle with something else just outside the picture.

Now, if you suppose that particle 1 came in as shown, can you determine the directions of all other tracks?

6. Indeed you can, as indicated in the margin.

There is another indication that our initial guess about the direction of track 1 is correct. There is a small arc-shaped track connected to track 1 near the entrance. It looks as if particle 1 collided with an electron and gave it enough energy for it to leave a visible track before it stopped. Such an electron is called a "knock-on" electron. The important thing is that a knock-on electron is produced when a rapidly moving primary particle strikes a nearly stationary electron. The electron is knocked forward, and although its track is subsequently bent by the magnetic field, the direction in which it starts is the same as the direction of travel of the primary particle. In the case at hand, the direction of the knock-on electron confirms that track 1 is coming into the chamber from the bottom of the page.

Now that the direction of travel of each particle has been established, you may try to determine the sign of the charge carried by each one. Since the tracks are quite straight, it may be necessary to place a ruler alongside of the tracks to determine which way they curve.

7. Unfortunately, many of the tracks are so short that the curvature cannot be determined. However, tracks 1, 2, and 6 definitely curve clockwise, so we know that these tracks were made by positive particles. This observation leaves us in a position to make a hypothesis about the entire event.

The only positive particles originally in the chamber are protons since these are the only positive particles present in ordinary matter, including both the walls and the hydrogen of the chamber. We therefore propose that particle 1 is an incoming proton which the beam knocks out of the chamber wall and which undergoes successive collisions with protons in the chamber. Each of these travels a short distance in the chamber before coming to rest and recombining with a free electron to form another hydrogen atom. In other words, this whole complicated event is assumed to be a series of simple elastic scattering events of the type

$$p^+ \text{ (moving)} + p^+ \text{ (at rest)} \longrightarrow p^+ + p^+ \text{ (both moving)}$$

Notice how the incoming track points between the two outgoing tracks in these elastic scattering events. This is necessary (but not sufficient) to ensure *conservation of momentum* in the collision. Can you explain this assertion?

8. Conservation of momentum requires that the vector sum of the outgoing momenta equal the incoming momentum. Even though we do not know their magnitudes, we do know the directions of the outgoing momenta. Their resultant must lie somewhere between them, so the incoming track must also point somewhere between them or momentum conservation could not possibly be satisfied.

You have probably seen, using air pucks or marbles, that a collision in free space between two objects of equal mass, one of which is initially at rest, always gives rise to an angle of 90° between the outgoing objects. If this is not familiar to you, perform a table top experiment with marbles or pucks.

If we look at a three-dimensional picture of the event we have been discussing, we see that at all four vertices the angle between the outgoing particles appears to be 90°. What conclusion can you draw from this observation?

9. You may conclude that these were collisions between particles of equal mass, with the target particle initially at rest. This is strong confirmation of the hypothesis proposed in step 7 as to the nature of this event.

If you wish to continue work on this picture, turn to Experiment 2 at the end of this unit.

The 90-degree rule holds exactly only for nonrelativistic collisions. A very simple proof of it follows.

By conservation of momentum

$m\vec{v}_a = m\vec{v}_b + m\vec{v}_c$

Cancelling the mass leaves

$\vec{v}_a = \vec{v}_b + \vec{v}_c$

So $\vec{v}_a$, $\vec{v}_b$ and $\vec{v}_c$ must form a triangle, as shown at right.

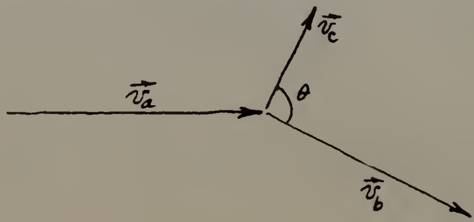
By conservation of energy, since kinetic energy is $\frac{1}{2} mv^2$,

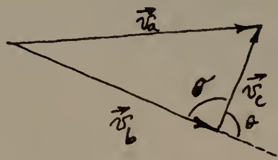
$\frac{1}{2} mv_a^2 = \frac{1}{2} mv_b^2 + \frac{1}{2} mv_c^2$

Cancelling the mass leaves

$v_a^2 = v_b^2 + v_c^2$

which, when v_a, v_b and v_c are the lengths of the sides of a triangle, is only satisfied if v_a is the hypotenuse of a right triangle. Then this is the usual Pythagorean relation for right triangles, so $\vec{v}_b$ and $\vec{v}_c$ must always be such that θ' is equal to 90°. If $\theta' = 90°$, θ must equal 90° also, as asserted above.





2.4 A Neutron Star

1. In Fig. 2.4, the experimental situation is the same as in Fig. 2.3, and several knock-on electrons as well as several negative beam tracks are visible. What are these beam tracks? They are pi minus mesons (π^-), among the most important particles of nuclear physics. Pi mesons may be positive, negative, or neutral, and they are carriers of the strong nuclear force, in much the same way that photons are the carriers of the electromagnetic force. In order to experiment with the strong force, physicists often use pi mesons as the incident beam particles in bubble chamber experiments.

Pi mesons are often called pions. Their behavior is discussed in Section 3.6 of this unit.

Notice that one beam track comes in and ends near the bottom of the picture (it is not connected to the small electron spiral which crosses it). Since no tracks leave the end point, can we conclude that no particles leave?

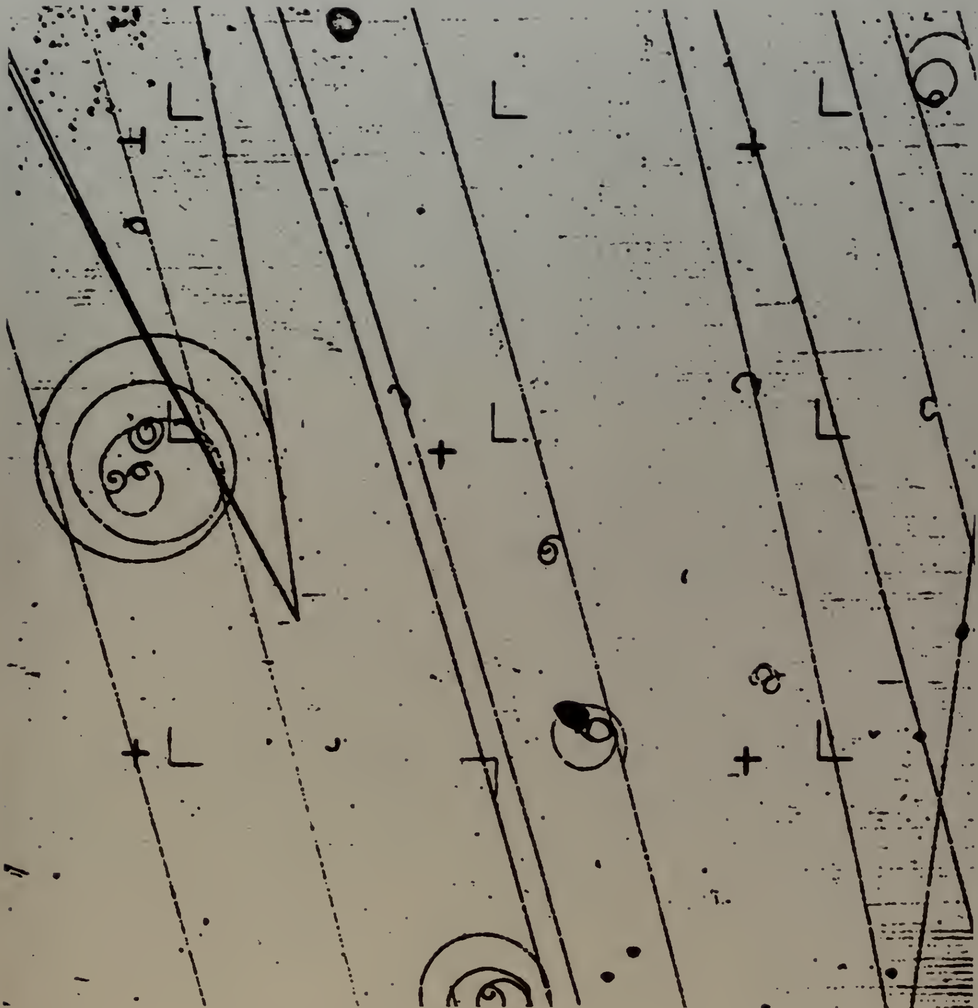


Fig. 2.4 Neutron star (actual size).

2. Neutral particles do not leave visible tracks; thus, all we can conclude is that any particles leaving this vertex are neutral.

Consider the law of *Conservation of Charge*. If a pi minus meson (π^-) hits a target particle and produces only neutral products, what must be the charge of the target?

3. It must be positive, and since the only positive particles in the chamber to start with are protons, we assume that the reaction is of the form pi minus and proton go to pi zero and neutron:

	π^- +	p^+ $\longrightarrow$	π^0 +	n^0
charge	-1	$+1$	0	0
total charge	0		0	

where the minus charge from the incoming pi meson moves over and cancels the plus charge on the proton, thus turning it into a

The charge, mass, and other properties of the elementary particles which are cited in these pages can all be found in the Table of Elementary Particles (Table 1.1).

neutron. Another possibility is pi minus and proton go to photon and neutron:

	$\pi^- + p^+ \longrightarrow \gamma^0 + n^0$			
charge	−1	+1	0	0
total charge	0		0	

This might ordinarily be all we could find out about such an event; however, in this case presence of a 3-prong "star" downstream is very suggestive. Could one of the neutral reaction products have produced that star? Let us consider the charge of the particles that made it.

4. Curvature tells us that there are two positive tracks and one negative track in the star, if we make the natural assumption that they are all leaving the vertex. Since they are all quite straight and solid-looking, it is unlikely that any could be electrons. Furthermore, the total charge after the reaction is positive, so that conservation of charge leads us to believe that the reaction creating these three particles occurred between a neutral particle, possibly from a π^-, p^+ collision, and a proton in the chamber.

At this point there could be several competing hypotheses as to what happened at the vertex of the star. For example, it could be that neutron and proton go to two protons and a pi minus:

	$n^0 + p^+ \longrightarrow p^+ + p^+ + \pi^-$				
charge	0	+1	+1	+1	−1
total charge	+1		+1		

or it might be that pi zero and proton go to proton, pi plus, and pi minus:

	$\pi^0 + p^+ \longrightarrow p^+ + \pi^+ + \pi^-$				
charge	0	+1	+1	+1	−1
total charge	+1		+1		

Conservation of momentum and energy should allow us to choose among the various competing possibilities.

5. Since an extension of the line from the end of the π^- to the vertex falls within the "V" of the 3-prong star, it would be quite possible for momentum conservation to be satisfied with either of the suggested hypotheses. Neither is there any obvious difficulty with conservation of energy, since the only additional particle created in either case is a pi meson with a mass of 140 MeV, and the incoming neutral particle could easily bring in that much energy as kinetic energy. Precise measurements of the vector momenta and a detailed comparison with the laws of conservation of momentum and energy can determine the masses and thus the identities of the unknown particles. This process is illustrated in detail in experiments 1 and 3 of this unit. In the case at hand, the first reaction is found by this method to be the correct one.

Inside the 28 GeV Proton synchrotron ring at CERN.

This reaction provides a good place to introduce another conservation law, the *conservation of baryon number.*

6. All particles which include a proton as one of the end products of their decay chain are called baryons and are assigned baryon number 1. Those particles which have an antiproton (see Sec. 3.4) at the end of their decay chains are called antibaryons and are assigned baryon number −1. All other particles have baryon number 0. Total baryon number is conserved in all reactions. A baryon can decay only if there exists a lighter baryon. Since the proton is the lightest of the baryons, it is not subject to decay. This fact is very important to us, since if protons were not stable, ordinary matter would not be stable either.

Consult the Table of Elementary Particles (Table 1.1) and then check to see if the law of conservation of baryon number is satisfied in the reactions in the picture under discussion.

7. This law is indeed satisfied, as can be seen from the following analysis:

Neutron production

	$\pi^- + p^+ \longrightarrow n^0 + \pi^0$
baryon number	0 +1 +1 0
total baryon number	+1 +1

Neutron-produced star

	$n^0 + p^+ \longrightarrow p^+ + p^+ + \pi^-$
baryon number	+1 +1 +1 +1 0
total baryon number	+2 +2

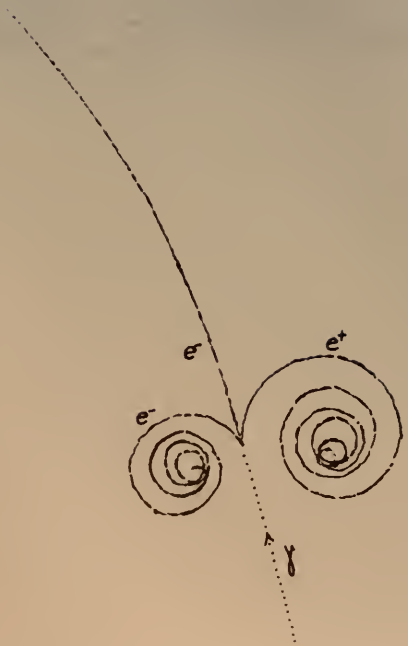
2.5 Pair Production

1. In Fig. 2.5 we see the transformation of energy into matter. The experimental situation is again the same as in Section 2.3, and you can again see about a dozen negative beam tracks traversing the chamber as well as a number of spirals due to knock-on electrons.

One of these spirals seems to go in the wrong direction to be made by an electron and yet strongly resembles an electron track in other respects. How do you account for this?

2. This is your first example of "antimatter." This track was made by anti-electron, or positron, which is like an electron except that it carries a positive charge (see Sec. 3.3).

Notice that the positron was produced in conjunction with two other particles that made negative tracks leaving the same vertex. This event was probably caused by a high-energy photon entering from the bottom of the picture. The photon apparently hit an atomic electron and gave it a large forward momentum (see the long negative track). In addition some of the energy of the photon went into the production of the positron-electron pair.



Although one electron has a straighter track than those of the electrons you have previously seen, its momentum is less than 70 MeV/c, while its range is at least 9 cm. The range versus momentum curves of Fig. L3 (p. 96) confirm that it is an electron. Since the photon is neutral, it does not produce ions along its path and therefore leaves no visible track in the chamber.

How much is the total charge of an electron-positron pair?

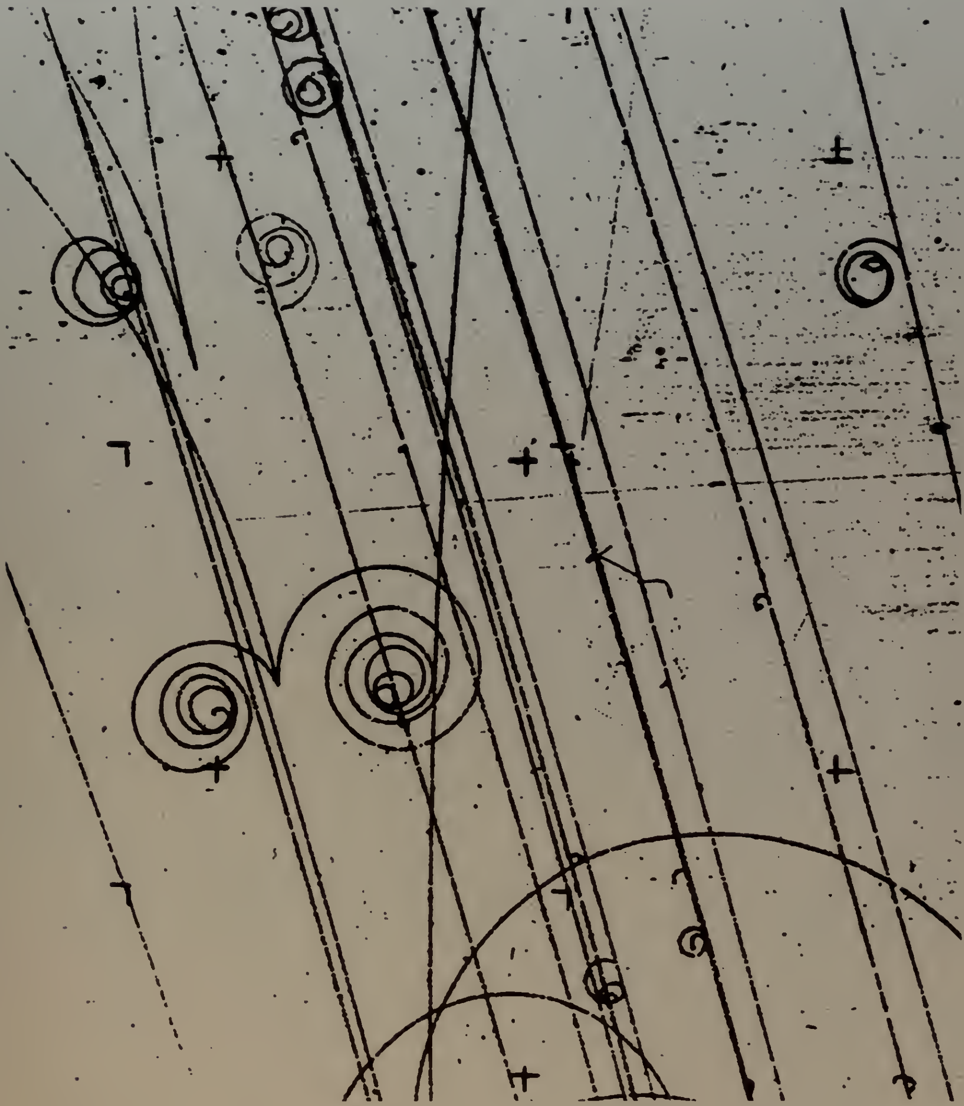


Fig. 2.5 Electron-positron pairs (actual size).

3. Zero. Thus *conservation of charge* is satisfied in the reaction photon goes to positron and electron (Remember that the extra electron was not produced by the photon but was simply set in motion by it):

	$\gamma^0 \longrightarrow$	$e^+ +$	e^-
charge	0	+1	−1
total charge	0	0	

Also notice that a positron is not produced alone, but in a pair with another particle, usually an electron. This interesting fact is discussed further in Chapter 3.

Another law that must be satisfied is *conservation of energy*. Consulting the Table of Particles, can you determine how much energy the incoming photon would need to produce just the mass of the electron and positron?

4. Looking at the Table of Particles, you see that the mass of the electron is 0.5 MeV, while that of its antiparticle, the positron, is the same. Therefore the photon must have an energy of at least 1.0 MeV to produce the electron-positron pair. Of course, in this instance the photon had additional energy which went into the kinetic energy of the pair and of the extra electron knocked out of the atom.

Even with the extra electron, it is possible that not all the energy of the photon has been used up. If this is the case, there must be a photon of lower energy among the reaction products. It is likely that the V downstream from our first event (Fig. 2.5) is produced by such a secondary photon. At any rate, this second V points directly back to the first vertex, as one would expect if it were due to a photon coming from the first vertex.

The second V is another electron-positron pair. What does the straightness of the tracks indicate about the momenta of these particles compared to those in the first pair?

5. The particles of the second pair have higher momentum than those of the first pair, since higher momentum causes a larger radius of curvature and thus straighter tracks. The reason for this difference is suggested by the picture. *Momentum must be conserved,* and in the first event most of the momentum of the incoming photon is carried off by the extra electron which made the long track and by the outgoing photon, if any, leaving very little momentum to be accounted for by the pair. In the second event, there is no additional electron, so the pair itself carries away all the incoming momentum.

Can you write the equations for this entire sequence of events?

6. Our final interpretation of this event is that photon and electron go to electron, electron-positron pair, and another photon, followed by the conversion of the second photon into an electron-positron pair.

$$\gamma + e^- \longrightarrow e^- + e^+ + e^- + \gamma'$$
$$\hookrightarrow e^+ + e^-$$

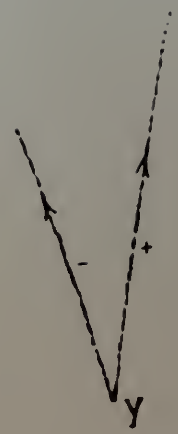
Pair production, the conversion of a photon into an electron-positron pair, usually takes place in a strong electric field. In the first event studied, the field is provided by the atomic electron with which the photon collided. This electron has a small mass and thus the collision causes it to go off at a high velocity. In the second event, the

field is provided by a proton, and with its large mass its velocity after the collision is so low that it slows down and stops again in the chamber, leaving a track that is so short that it cannot even be seen.

2.6 Strange Particle Production and Decay

1. Here we introduce some of the exotic new particles discovered since 1947, particles that have led high-energy physicists to many unexpected questions, some of which are the most interesting questions in physics today.

The picture in Fig. 2.6 was taken in the same bubble chamber as the others, using a beam of pi minus mesons (π^-) entering at the bottom of the photograph. You can see a beautiful electron spiral and a few knock-on electrons, but the most prominent tracks in the chamber are two V's, whose vertices apparently point toward the end of the beam track.



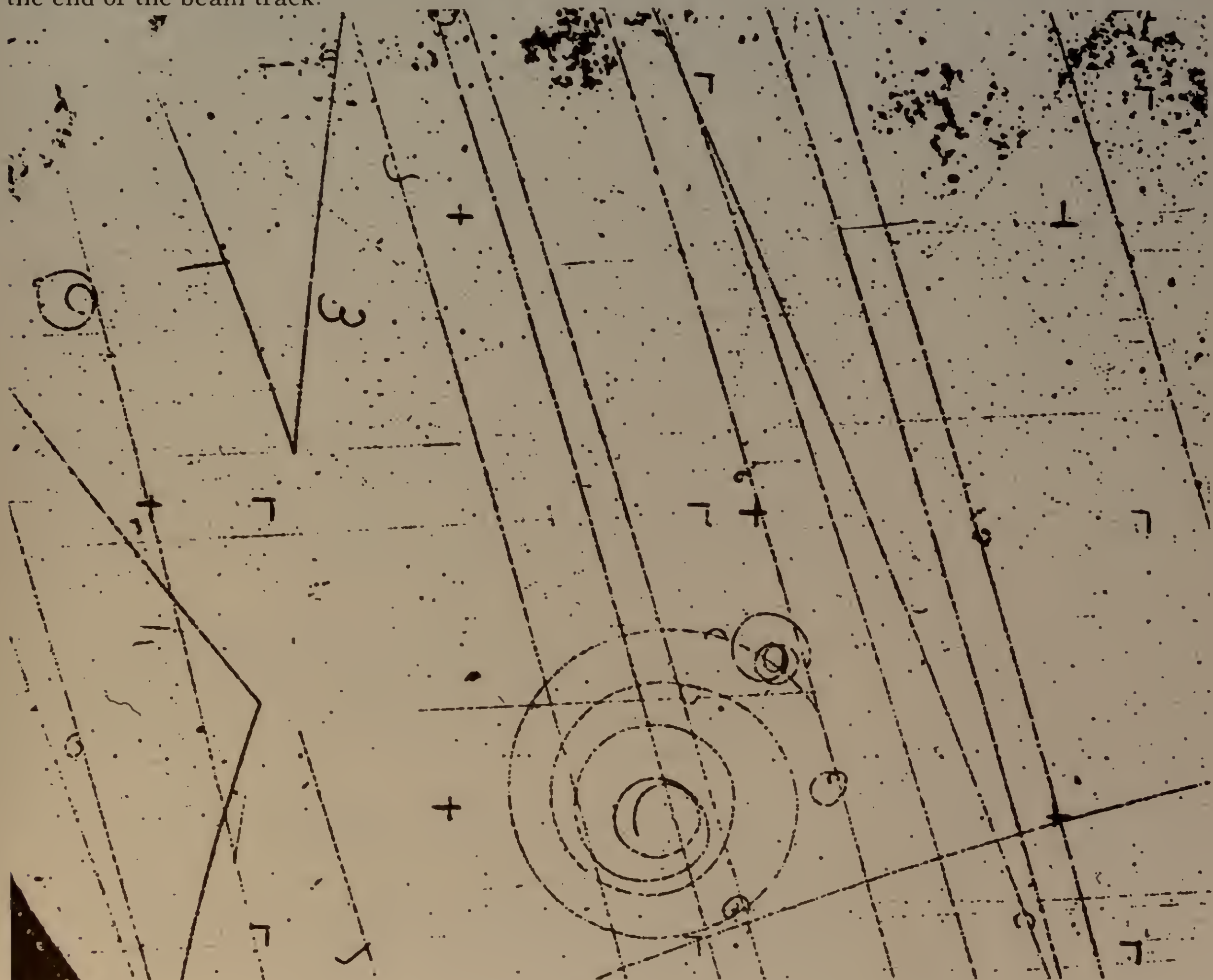
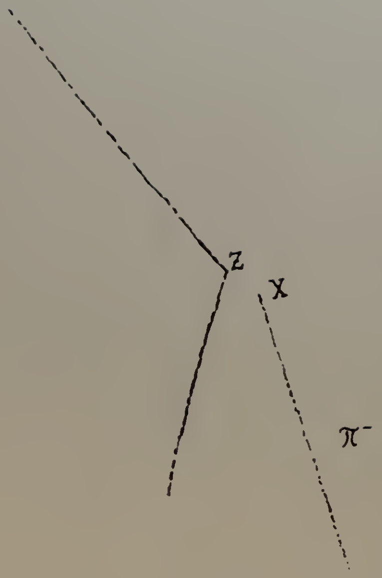


Fig. 2.6 Strange particles (actual size).



Recalling Section 2.4, can you tell what particle the π^- interacts with at the end of this beam track?

2. It interacts with a proton from the hydrogen so that *conservation of charge* is readily satisfied by reactions of the form pi minus and proton go to neutrals:

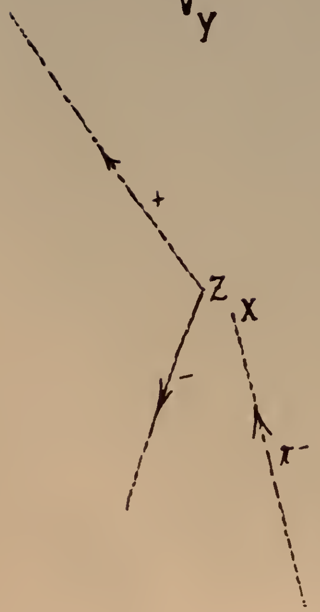
$$\pi^- + p^+ \longrightarrow \text{neutrals}$$

Study each of the V's, comparing each track with a straightedge to determine the direction of its curvature. Can you tell the charge of each particle?

3. On the reasonable assumption that the visible tracks go away from the vertex of each V, the charges must be as indicated on the middle sketch in the margin. Apparently the V's are produced by reactions involving an incoming neutral particle, since no incoming track is visible. If such a reaction involved the collision between the neutral particle and a proton, the total charge of the outgoing tracks would have to be positive, so that possibility can be ruled out. On the other hand if each V were produced by the decay of a neutral particle, *conservation of charge* would be nicely satisfied:

	neutral $\longrightarrow$	positive +	negative
charge	0	+1	−1
total charge	0	0	

Next you can check to see if the track directions are consistent with the hypothesis that two neutral particles are produced at X and then proceed to Y and Z where they decay. What law would you use to make such a test?

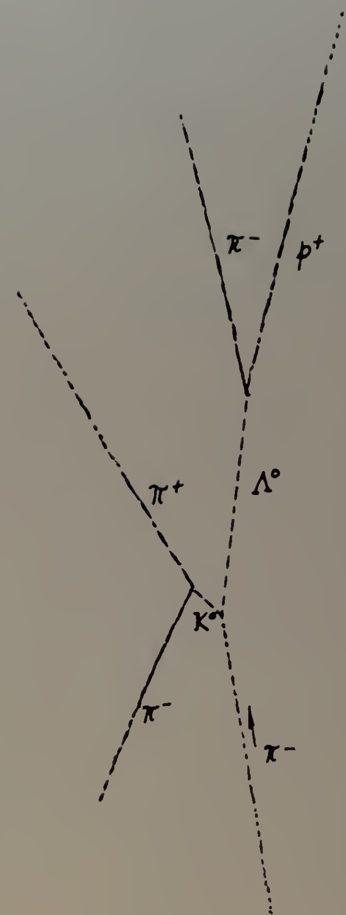


4. The law of *conservation of momentum* requires that the incoming track at each V, if extended, must pass between the two outgoing tracks. This is the case for the neutral V produced at X as well as for the two charged V's in this picture, so there is a possibility that the hypothesis in step 3 is correct.

To make a conclusive test you would have to measure the momenta of all particles and make a precise numerical check of conservation of momentum. The momenta of the neutral particles are assumed to be the same at Y and Z as at X. Can you explain this assumption?

5. In the first place, a magnetic field exerts no force on an uncharged particle, so the neutral tracks will be straight. In the second place, neutral particles do not ionize the hydrogen, and therefore they do not lose energy as they travel. This means that unlike charged particles, they will maintain constant momenta along their tracks.

The law of *conservation of energy* can then be applied at each vertex to test various hypotheses concerning the identities of the particles. When this is done, it is found that the neutral particles are of a kind that you have not seen before.



6. The actual nature of the event is sketched in the margin. It includes a kay zero meson (K^0) and a lambda zero baryon (λ^0), which are the first particles you have encountered with the property called strangeness. In the Table of Particles, an integer value is given for the strangeness of each particle. The physical meaning of strangeness will be discussed in greater detail in Chapter 4; for the moment, it is important to know that the total strangeness is always conserved in strong or electromagnetic interactions, but not in weak interactions. Notice from the equation below how *conservation of strangeness* holds at the production vertex of this event, where pi minus and proton go to kay zero and lambda zero:

	π^-	$+\ p^+$	$\longrightarrow$	K^0	$+\ \Lambda^0$
strangeness	0	0		+1	−1
total strangeness	0			0	

Since strangeness is conserved here, which of the four basic interactions do you think caused this reaction?

7. The reaction at the production vertex is a *strong interaction*, because the products are strongly interacting particles, and *strangeness is conserved*. Measurement shows that the λ^0 and K^0 originate right at the end of the pi meson track. This is consistent with the strong interaction, which takes place in 10^{-23} sec, about the time it takes for the high-velocity pi meson to cross the diameter of the target proton.

Next you should test the decay events in the same way, consulting the last of our marginal sketches to identify the particles produced. Is strangeness conserved there also?

8. The decay on the left has the form kay zero goes to pi minus and pi plus:

	K^0	$\longrightarrow$	π^-	$+\ \pi^+$
strangeness	+1		0	0
total strangeness	+1		0	

and the decay on the right has the form lambda zero goes to pi minus and proton:

	Λ^0	$\longrightarrow$	π^-	$+\ p^+$
strangeness	−1		0	0
total strangeness	−1		0	

Thus conservation of strangeness is *violated* in these decays. This is because the decays take place via the *weak interaction*, while strangeness only needs to be conserved in strong and electromagnetic interactions. It is a "partially conserved" quantity.

$\frac{3\text{ cm}}{3 \times 10^{10}\text{ cm/sec}} = 10^{-10}$ sec

Notice how slowly the weak interaction takes effect. The particles in question can travel a few centimeters before they decay, so they live for times of the order of 10^{-10} sec. The weak interactions are about 10^{13} times slower than the strong interactions.

Finally you will want to check *baryon conservation* and *charge conservation* in the proposed reactions.

9. As shown below, baryon number and charge are conserved in every reaction, as they must be since these are absolutely conserved quantities.

Production

	$\pi^- + p^+ \longrightarrow K^0 + \Lambda^0$			
baryon number	0	+1	0	+1
total baryon number	+1		+1	
charge	−1	+1	0	0
total charge	0		0	

Decays

	$K^0 \longrightarrow \pi^- + \pi^+$		
baryon number	0	0	0
total baryon number	0	0	
charge	0	−1	+1
total charge	0	0	

	$\Lambda^0 \longrightarrow \pi^- + p^+$		
baryon number	+1	0	p^+
total baryon number	+1	+1	
charge	0	−1	+1
total charge	0	0	

2.7 A K^- Meson Interaction

1. In Fig. 2.7 the bubble chamber is the same, but the beam has been changed to kay minus mesons (K^-). These are produced along with many other particles by letting the protons inside an accelerator smash into a target. Then, by means of magnetic and electric fields, the K^- particles with the desired momentum are selected and brought to the bubble chamber.

Ignoring other tracks, let us concentrate on the event sketched in the margin. Arrows are on the tracks to indicate which way the particles travel. Do you agree with this interpretation?

2. This seems reasonable, since the beam track can be identified by its direction, and we expect tracks to be leaving, not approaching, its end. By actual measurement, the equations of this

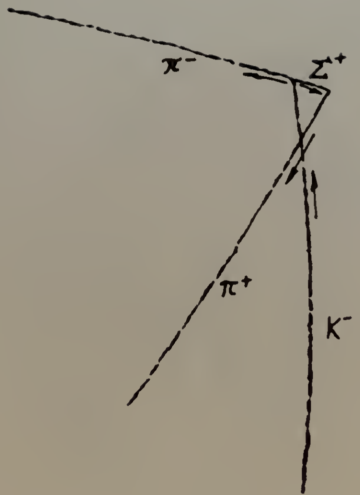
Fig. 2.7 A K^- meson interaction (actual size).

If you look at this picture on the 3-D slide wheel, turn the View-master upside down to make the directions identical.

event have been found to be kay minus and proton go to pi minus and sigma plus, followed by sigma plus goes to pi plus and neutron:

$$K^- + p^+ \longrightarrow \pi^- + \Sigma^+$$
$$\quad\quad\quad\quad\quad\quad\quad\quad \hookrightarrow \pi^+ + n^0$$

Can you label the visible tracks?



Although high energies were required to produce the K mesons in the beam, the reaction studied here actually takes place at low energy.

3. The proper labelling is shown in the sketch in the margin. The neutron, being neutral, and the proton, being at rest, leave no tracks.

Notice that the π^- and Σ^+ tracks are collinear (lie along the same line), which suggests that their momenta may be equal and opposite. What would that say about the momentum of the incoming K^- meson?

4. If the momenta of the π^- and the Σ^+ are indeed equal and opposite, then the total momentum of the reaction products is zero. *Conservation of momentum* then requires that the total momentum of the incoming particles also be zero. Since the target proton is at rest, this implies that the incident K^- meson must also come to rest before the reaction. Like all charged particles traveling in matter, the K^- meson slows down as it travels and can eventually stop. When it does so it is attracted to a nearby proton with which it can react. Its momentum at that time is not strictly zero, but it is so low (perhaps 0.001 MeV/c) that we cannot possibly measure it directly, and we say that the reaction took place "at rest."

According to the law of conservation of momentum, the momentum of the incoming K^- meson must equal the vector sum of the momenta of the outgoing particles. But the momentum of the K^- must lie along its path, and the resultant of the π^- and Σ^+ momenta must lie in the direction of the larger one, because they are collinear. Thus the incoming and outgoing momenta are apparently in different directions, and the only way they could be equal is for them both to be zero. This would require the momenta of the π^- and the Σ^+ to be not only opposite in direction, but also equal in magnitude, as suggested above.

You can test these events to see if appropriate conservation laws are obeyed.

5. In the production reaction, a strong interaction, *charge*, *baryon number*, and *strangeness* are conserved, as indicated below:

	K^-	$+\ p^+$	$\longrightarrow\ \pi^-$	$+\ \Sigma^+$
charge	−1	+1	−1	+1
total charge	0		0	
baryon number	0	+1	0	+1
total baryon number	+1		+1	
strangeness	−1	0	0	−1
total strangeness	−1		−1	

In the decay of the Σ^+, a weak interaction, charge and baryon number are conserved, but strangeness is not, as seen below:

	Σ^+	$\longrightarrow$	π^+	+	n^0
charge	+1		+1		0
total charge	+1			+1	
baryon number	+1		0		+1
total baryon number	+1			+1	
strangeness	−1		0		0
total strangeness	−1			0	

Aerial view of the AGS 80-inch Liquid Hydrogen Bubble Chamber building at Brookhaven National Laboratory.

CHAPTER THREE

The Story of Particles

3.1 The Situation in 1932

Let us briefly review the state of our knowledge of the composition of matter in May of 1932, when Chadwick had just discovered the neutron. The elementary particles known at that time are listed below:

TABLE 3.1 LIST OF PARTICLES KNOWN IN 1932

Particle	*Symbol*	*Mass* (MeV)	*Charge* (unit charges)
Photon	γ	0	0
Electron	e^-	0.5	−1
Proton	p^+	938	+1
Neutron	n^0	938 ±4	0

It was agreed that the atom is composed of a nucleus surrounded by electrons which are bound to it by electric forces. It was possible to explain the properties of the elements, including the way in which they form chemical compounds, in terms of the behavior of these electrons. The basic principles of chemistry were completely established in accordance with this model of the atom. Not only that, but atomic nuclei were believed to be composed of protons and neutrons, and this could account for the observed atomic weights as well as many other properties of nuclei. Photons were the particles that carry light and other electromagnetic disturbances, and their emission and absorption, as well as their propagation through space, were quite well understood. Of course there was much to be done in the way of applying this basic knowledge to various specific situations, but it seemed that the list of elementary particles might be complete. There was some hope that a complete understanding of matter could be obtained on the basis of the particles known at that time.

But even then there were points of difficulty, points which may have suggested that there was more to come. For one thing, no one knew what held the nucleus together in the face of the electrostatic repulsion between its protons. And there were peculiar difficulties with the theory of the electron, which was magnificent in most respects but which seemed to contain some extra mathematical consequences that had no physical meaning. Also, there were phenomena associated with radioactive decay, when beta particles were emitted from nuclei, which no one was able to explain using currently available theories.

A beta particle is an electron or a positron (e^- or e^+) emitted from a nucleus in radioactive decay. Decay processes involving the emission of beta particles are called beta decay.

3.2 The Neutrino (ν)

The problem of beta decay was a particularly unpleasant one because it threatened one of the most cherished laws of physics: the law of conservation of energy. A typical beta decay process is bismuth 210 which decays to polonium 210 and an electron:

$$\mathrm{Bi}(210) \longrightarrow \mathrm{Po}(210) + e^-$$

Experimental study of this process shows that the kinetic energy of the polonium nucleus is negligibly small, while that of the emitted electron (e^-) can have any value from 0 to 0.65 MeV. The total energy of the bismuth nucleus is due to its mass, and equals 195,595.59 MeV, but the total energy of the decay products, the polonium and the electron, is observed to have any value from 195,594.94 MeV to 195,595.59 MeV. Since the total energy of the decay products is often *less than* the total energy of the original bismuth nucleus, some energy apparently vanishes completely!

In 1930, a brilliant young Austrian physicist named Wolfgang Pauli made the tentative suggestion that in beta decay there might be another particle emitted in addition to the electron. According to his calculations, this particle, the neutrino (ν) would have to have a very small mass and zero charge. The fact that it had not been previously detected could be explained if it had a high penetrating power. The Italian physicist Enrico Fermi picked up this idea and worked out the theory in detail, finally publishing it in 1933. In the Fermi theory of beta decay, the missing energy was carried off by the neutrino, so the correct equation for the reaction discussed above is bismuth 210 goes to polonium 210, an electron, and a neutrino:

The Greek letter nu (ν) is used here to represent any neutrino, although we shall see later that there are actually four different kinds of neutrino, ν_e, ν_μ, $\bar{\nu}_e$ and $\bar{\nu}_\mu$.

Neutrino is a word derived from the Italian, meaning "little neutral one."

$$\mathrm{Bi}(210) \longrightarrow \mathrm{Po}(210) + e^- + \bar{\nu}_e$$

This theory explained the energy variation of the emitted electrons so well that the world of physics accepted the existence of the neutrino long before it could be observed in any direct way.

If a neutrino was indeed carrying off the missing energy in beta decay, it must also carry off some momentum. In order to test this

Fig. 3.1 Wolfgang Pauli in 1929.

possibility further, experiments were devised to measure the very small momentum of the recoil nucleus as well as that of the electron. This would allow the calculation of the missing momentum, which could then be compared with the momentum presumed to be carried off by the neutrino. Such experiments were eventually successful in the late 1930's, but they still did not satisfy the need for experimental detection of the free neutrino itself.

To detect the presence of a neutrino, it was necessary to arrange a collision or other interaction between this particle and a nucleus in some target material. However, on the average, a single neutrino would have to travel 50 light years through solid lead before any such interaction would occur. Thus, the experiment required a very intense source that would supply many neutrinos per second. In fact it was calculated that a flow of 10^{16} neutrinos per minute through a ten-ton detector would be just barely adequate to ensure that a measurable number of the particles could actually be detected in an experiment. Where could such an intense beam of neutrinos be found? Only at one of the large reactors of the Atomic Energy Commission, such as the ones at Hanford, Washington, or

Zurich, December 4, 1930

Dear radioactive ladies*
and gentlemen,

I beg you to most favorably listen to the carrier of this letter. He will tell you that, in view of the "wrong" statistics of the N and Li^6 nuclei and of the continuous beta spectrum, I have hit upon a desperate remedy to save the laws of conservation of energy and statistics. This is the possibility that electrically neutral particles exist which I will call neutrons, which exist in nuclei, which have a spin ½ and obey the exclusion principle, and which differ from the photons also in that they do not move with the velocity of light. The mass of the neutrons should be of the same order as those of the electrons and should in no case exceed 0.01 proton masses. The continuous beta spectrum would then be understandable if one assumes that during beta decay with each electron a neutron is emitted in such a way that the sum of the energies of neutron and electron is constant. . . .

I admit that my remedy may look very unlikely, because one would have seen these neutrons long ago if they really were to exist. But only he who dares wins and the seriousness of the situation caused by the continuous beta spectrum is illuminated by a remark of my honored predecessor, Mr. Debye, who recently said to me in Brussels: 'O, it is best not to think at all, just as with the new taxes.' Hence one should seriously discuss every possible path to rescue. So, dear radioactive people, examine and judge. Unfortunately I will not be able to appear in Tubingen personally, because I am indispensable here due to a ball which will take place in Zurich during the night from December 6 to 7.

Your most obedient servant,
W. Pauli

**The "neutrons" referred to are the present-day neutrinos. The "radioactive lady" is Lise Meitner.*

In the equation describing a possible reaction, we can move any particle to the opposite side of the equation, replace it by its antiparticle, and obtain another possible reaction. This is a general property of particle reactions called crossing symmetry.

The process of positive beta decay inside a nucleus can be represented by

$$p^{+} \longrightarrow n^{0} + e^{+} + \nu_{e}$$

If we move the neutrino to the opposite side of the equation and replace it by an antineutrino we get

$$\overline{\nu}_{e} + p^{+} \longrightarrow n^{0} + e^{+}$$

which is the reaction that Reines and Cowan set out to observe.

Savannah River, South Carolina. These had been built for production of nuclear weapons, but a by-product of their operation, due to their high power levels, was the production of many neutrinos in the beta decay of the various radioactive isotopes within. Clyde Cowan and Frederick Reines of the Los Alamos Laboratory conducted experiments at each of these reactors to find evidence for the reaction neutrino and proton go to neutron and positron:

$$\overline{\nu}_{e} + p^{+} \longrightarrow n^{0} + e^{+}$$

If one could detect a neutron and a positron with the proper energies, and prove that they had been produced at precisely the same time, one could say that a neutrino-induced reaction had been observed. The results of the first experiment, at Hanford in 1953, gave probable but not conclusive evidence of such a reaction. Then in

Fig. 3.2 Scintillation counter detector used by Reines and Cowan in their first neutrino experiment at Hanford, Washington, in 1953. The counter, which weighed ten tons, is the cylindrical object near the bottom.

1956 an improved experiment at Savannah River proved successful: the desired reaction was observed about once every twenty minutes.

Later experimental work has shown that there are both neutrinos and antineutrinos, (ν and $\bar{\nu}$), differing in the direction in which they spin about their axes. Furthermore, there seem to be two different kinds of neutrino-antineutrino pairs: one, nu ee (ν_e), belonging to the electron family, and the other, nu mu (ν_μ), belonging to the muon family. These are discussed further in the section on muons.

3.3 The Positron (e^+)

Among the great theorists of the 1920's was a young Englishman, Paul A. M. Dirac, who was appointed a postdoctoral fellow in mathematics at St. John's College of Cambridge University. His contributions to mathematical physics were many, and to this day his book *The Principles of Quantum Mechanics* is the basic work in the field.

In 1928 Dirac published a beautiful paper proposing a new theory of the electron, a theory that combined ordinary quantum mechanics with Einstein's theory of special relativity. From this relativistic theory of the electron he was able to make detailed calculations of many atomic phenomena with accuracy and elegance, so that his theory soon gained general acceptance. It was for this work that he received his Nobel prize, shared with Erwin Schrödinger in 1933.

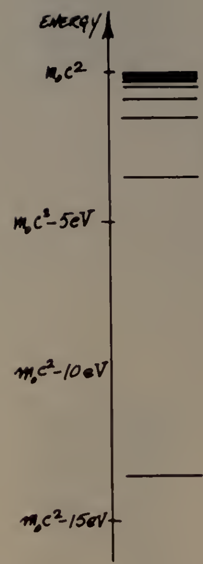


Fig. 3.3 Allowed states of the electron in a hydrogen atom (observed).

To understand the implications of this theory we must first review some of the facts of atomic physics. You may recall that one of the basic results of quantum theory is that an electron can only have certain "allowed" values for its energy. For an electron bound in a hydrogen atom, the allowed states are simply the discrete stationary states prescribed by the Bohr model and plotted in Fig. 3.3. No other values are ever found. On the figure, m_0c^2 is 0.5 MeV, the rest energy of the electron.

For a free electron, there are many more allowed states than there are for a bound electron. In fact, in one cubic centimeter of space there are about 10^{24} available states with energies between 0 and 1 eV alone. If we increase the volume of space to which we restrict the electron, the number of allowed states increases, as does the number per unit energy interval. For a free electron in infinite space, the allowed states approach a continuous set, corresponding to all kinetic energies from zero on up. Including the rest energy of the electron, the total energy of these allowed

The horizontal axis has no meaning on an energy level diagram—all the information is contained along the vertical axis. However, for the sake of visual appearance it is customary to draw the diagram as we have here.

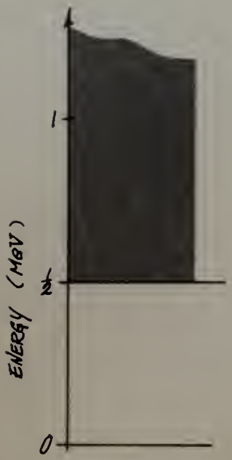


Fig. 3.4 Allowed states of the free electron (observed).

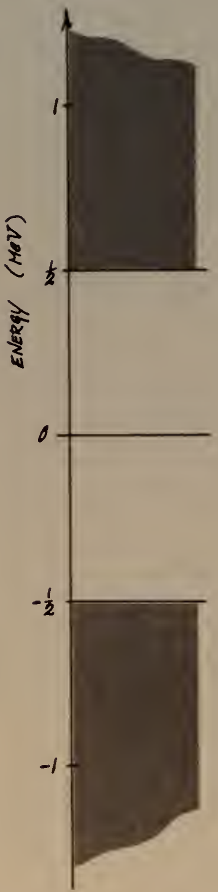


Fig. 3.5 Allowed states of the free electron (Dirac theory).

According to this model, if an electron drops into a hole, neither the electron nor the hole is observable any more. All that remains is the energy lost by the electron in the process, energy which normally appears in the form of gamma rays. In this kind of situation it is customary to speak of the electron and the hole as annihilating each other.

states ranges from 0.5 MeV on up without limit. This can be represented by an energy level diagram as shown in Fig. 3.4, where the allowed states are indicated by shading because they are so close together. It is important to remember that each allowed energy level has a definite capacity for electrons, just like the electron shells in an atom. The capacity of a particular level may or may not be used, but it is definitely limited: this is commonly called the exclusion principle.

Now the Dirac theory, elegant though it was, contained a problem: not only did it correctly predict all the observed energy states of the free electron, but it also predicted that there were allowed states with negative total energy! As Fig. 3.5 shows, it predicted states with total energy less than *minus* 0.5 MeV as well as the commonly observed states with energy greater than *plus* 0.5 MeV Since the actual meaning of a negative total energy was puzzling and such states certainly had not been observed, an explanation was in order, and it went as follows.

Suppose that all the negative energy states were full. This would of course require infinitely many electrons, but there is no physical reason to prevent our assuming the presence of that many. Furthermore, if these states remained full all the time, no electron would ever enter one or leave one, and there would be no way in which these states could be observed. Now, suppose that a single state in this "Dirac sea" of filled states were empty. Then there would be one electron less than normal in the world. Since the electron has negative charge, there would also be one negative charge less than normal, or one could say that there was one positive charge more than normal. A "hole" in a negative sea acts like a positive charge! Since the proton was the only fundamental particle known with a positive charge, perhaps protons were nothing more than holes in a sea of electrons. With one stroke, this would provide a theory that explained not only the behavior of electrons but that of protons as well.

Unfortunately for this hypothesis, further calculations by J. Robert Oppenheimer and by Dirac himself showed that the stability of ordinary matter could not be accounted for by this model: the available electrons would drop into the holes in times of the order of 10^{-10} seconds, or in other words, all the electrons and protons in the world would promptly annihilate one another. Therefore, it was proposed that protons should be regarded as quite separate from electrons and that Dirac's holes, if they existed at all, might represent a new type of particle, with a mass equal to that of the electron but with a positive charge.

The "positive electron" or positron (e^+) might be produced in a pair with an ordinary electron (e^-) when an energetic photon collided with an electron in one of the negative energy states as

Fig. 3.6 Pair production.

(a) 1-MeV photon hits electron in negative sea.

(b) Electron moves up to positive energy state, leaving "hole" (positron) behind.

shown in the above diagrams. The photon must give the target electron at least 1 MeV of energy in order to knock it up into one of the allowed positive energy states, thus leaving a hole behind.

The net effect of such a process is the disappearance of a photon and the appearance of an electron-positron pair, so we can write the equation as photon goes to electron and positron:

$$\gamma \longrightarrow e^- + e^+$$

In recent years, physicists have stopped talking about the unobservable "Dirac sea" of negative energy states for electrons; they only talk about the positrons and the electrons themselves. The mathematics remains the same, but the interpretation has changed.

All this talk of positive electrons would have remained mere speculation were it not for the experimentalists, who were busy in

their own efforts. The Wilson cloud chamber had been applied to the study of cosmic rays by D. Skobelzya at the Polytechnic Institute in Leningrad in 1929. Then, on August 2, 1932, Carl D. Anderson, a 27-year-old postdoctoral fellow working with Professor Robert A. Millikan at the California Institute of Technology, saw a cloud chamber track that had been left by the first positron ever to be identified. His first report was cautious, speaking only of a "positively charged particle comparable in mass and magnitude of charge with an electron," but a number of experiments during the following year quickly confirmed the discovery of the positron. It is interesting that within one year of Anderson's first observation at least seven papers were published on related experiments. These included work by Irene Curie and F. Joliot in France and by P. M. S. Blackett and G. Occhialini at the Cavendish Laboratory in England. Apparently then, as now, a new discovery aroused physicists to feverish excitement.

Fig. 3.7 An early model of the cloud chamber, invented by C. T. R. Wilson of Scotland in 1912. Charged particles pass through the chamber, leaving visible tracks, which can then be photographed to provide a permanent record. This device was the forerunner of the present-day bubble chamber.

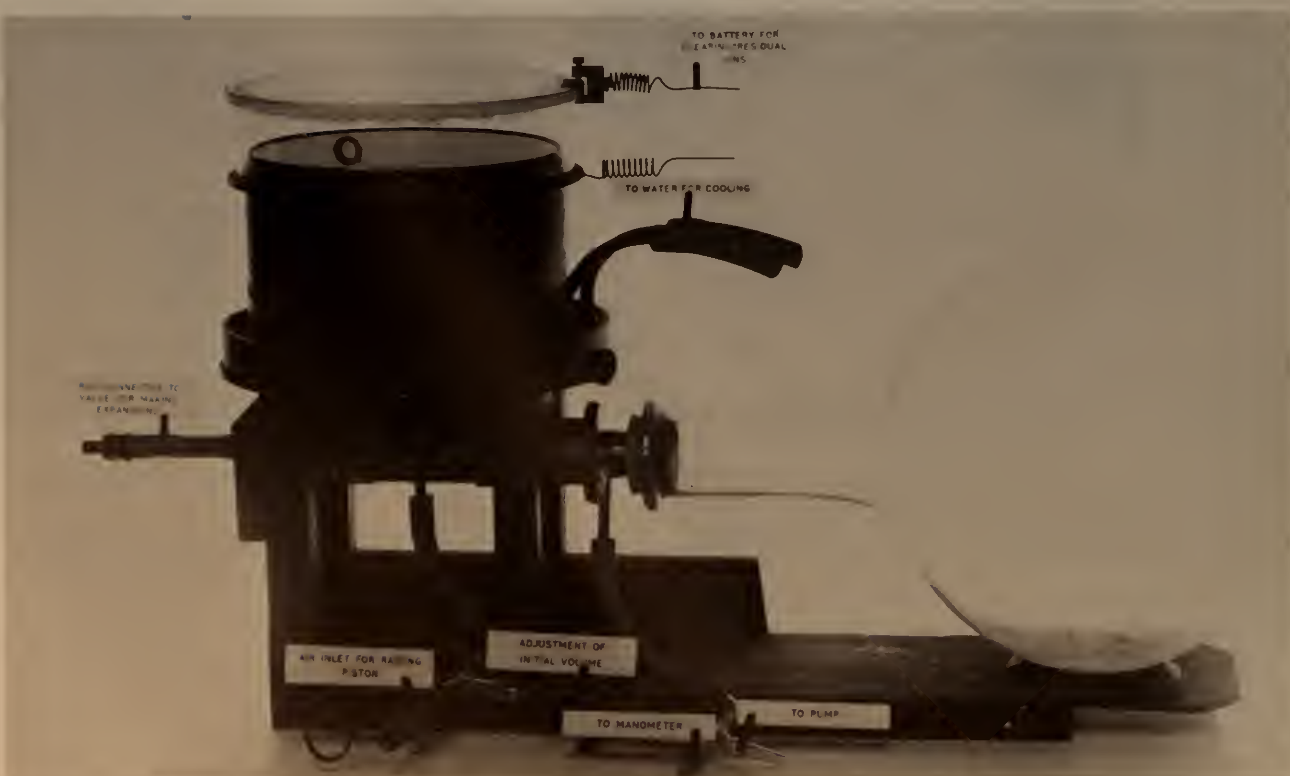


Fig. 3.8 Electron-positron pairs produced in a cloud chamber. Two views of the chamber are photographed simultaneously to allow complete three-dimensional information to be obtained about the tracks.

"Antimatter" could be made of positrons and antiprotons in the same way that ordinary matter is made of electrons and protons. Antiparticles are not the opposite of "ordinary" particles, but are simply particles with certain properties that are opposite to those of the "ordinary" particles. "Ordinary" particles are so named because it just happens that our own world is made of them rather than of anti-particles, although it is quite possible that somewhere else in space there might be a world made of antiparticles. The only exotic thing about this situation is that if a particle and its antiparticle meet, they annihilate each other, and their mass is converted to energy. Thus, in the collision between a large scale object made of antimatter with one made of ordinary matter, the entire mass would immediately be converted to energy.

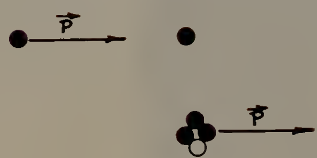
3.4 The Antiproton ($\bar{p}^-$)

The discovery of the positron left no doubt that the antiproton also existed, although this particle was not actually observed until more than twenty years later. A particle of "antimatter" had been observed in at least one instance, that of the positron, and there were strong theoretical reasons to believe that every particle has its corresponding antiparticle. In fact, Dirac's 1931 paper, in which he first mentioned the antielectron (positron), also mentioned the antiproton.

The reason for this delay was strictly technological: to make an antiproton requires a beam of particles with an energy of about 6 GeV, and until 1954 energies of that magnitude were available only in cosmic rays. Unfortunately, cosmic rays cannot be controlled, and such high energies are relatively rare, so that no antiprotons were positively identified in cosmic ray experiments, although at least three possible candidates were found.

Remember that one GeV (Giga-electron volt) equals one thousand million electron volts, sometimes called BeV.

In 1954, a new proton accelerator was completed with an energy chosen just large enough to produce antiprotons. This was the famous 6.2-GeV Bevatron at the Lawrence Radiation Laboratory of the University of California, Berkeley. It will be of interest to see how this energy was chosen and to consider the antiproton experiment in some detail.



To produce an antiproton, we must simultaneously produce a new proton: they come in pairs just as positrons and electrons do. However, instead of using photons to strike the target material as we do in producing electron-positron pairs, we use high-energy protons. A possible reaction is then

	p^+	$+\ p^+$	$\longrightarrow$	p^+	$+\ p^+$	$+\ p^+$	$+\ \bar{p}^-$
charge	+1	+1		+1	+1	+1	−1
total charge	+2			+2			
baryon number	+1	+1		+1	+1	+1	−1
total baryon number	+2			+2			

Notice that total charge and baryon number are conserved in this reaction. Of course, the incident proton must bring in enough energy to satisfy energy and momentum conservation also. The required energy must be at least 1876 MeV (2 × 938 MeV) in order to provide the mass of the two new particles that are created, but momentum conservation requires that it be much larger than this.

Relativistically, the total energy of a particle with mass m and momentum p is given by $\sqrt{(mc^2)^2 + (pc)^2}$
Thus, if E is the total energy of the incident proton, m the mass of the target proton, at rest, and p the momentum both before and after the collision, we can write the law of conservation of energy as follows:

$$\begin{Bmatrix}\text{energy of incident}\\ \text{proton}\end{Bmatrix} + \begin{Bmatrix}\text{energy of}\\ \text{target}\end{Bmatrix} = \begin{Bmatrix}\text{energy of product}\\ \text{particle of mass 4m}\end{Bmatrix}$$

$$E + mc^2 = \sqrt{(4\,mc^2)^2 + (pc)^2}$$

Square both sides:

$$E^2 + 2\,E(mc^2) + (mc^2)^2 = 16(mc^2)^2 + (pc)^2$$

Substitute E^2 for its equivalent, $(mc^2)^2 + (pc)^2$, on the right:

$$E^2 + 2\,E(mc^2) + (mc^2)^2 = 15\,(mc^2)^2 + E^2$$

Collect terms:

$$2E\,(mc^2) = 14\,(mc^2)^2$$

Divide by $2(mc^2)$:

$$E = 7\,(mc^2)$$

which is the total energy required of the incident proton. Since the kinetic energy E_k is the total energy minus the rest energy mc^2,

$$E_k = 6mc^2 = 6 \times 938\text{ MeV} = 5728\text{ MeV} = 5.7\text{ GeV}$$

Ordinarily a high-energy incident proton of mass m and momentum $\vec{p}$ strikes a target proton of mass m which is at rest. In the simplest case, when there is just barely enough energy to produce a $\bar{p}$, the reaction products move off together much like a single "particle" of mass $4m$. The law of conservation of momentum requires that the total momentum after the collision equal the total momentum just before the collision, which had a magnitude p. Using this fact together with the law of conservation of energy, we find that the kinetic energy of the incident proton must be at least 5.7 GeV for this process to be possible. (If the incident energy is larger than this value, the product particles do not stick together, but use the extra energy to fly apart from one another.) Thus the specification of an energy of 6.2 GeV for the Bevatron gave a 10% margin above the absolute minimum for antiproton production.

The apparatus used in this search is typical of those experiments in high-energy physics that use electronic counters. The principles on which it operates are those described in Section 1.6. First, a target is flipped into the 6-GeV proton beam inside the accelerator, producing a great mixture of particles of various types and momenta. Then bending magnets are used to send particles of different momenta and different charge on different paths. The final step in this case is to take the beam of particles with the right momentum and charge and find out if it includes any particles with the correct

mass to be antiprotons. Because the mass of a particle with known momentum can be calculated from its velocity, this step is carried out by directing the beam at a series of counters which can detect velocity very accurately. These counters signal when triggered by a particle whose velocity suggests that it may be an antiproton. The correct signals must be obtained from all the counters in the apparatus before a particle passing through it is identified as an antiproton.

Within a year after the Bevatron first went into operation, Emilio Segré, Owen Chamberlain, and their collaborators put this detection system into operation and found the antiproton. In fact, by the year's end, their counters had given "yes" signals corresponding to more than sixty antiprotons.

3.5 The Antineutron ($\bar{n}^0$)

Once the idea of antiparticles became firmly established due to observation of the positron, the possibility of the existence of an antineutron was strongly suggested also, although the word does not appear in the literature until 1937. However, at that time, the neutron itself was newly discovered, and the possibilities it presented dominated the work of experimental physicists for some time. Not only that, but the production of an antineutron had the same energy difficulties as the production of an antiproton, so it is not surprising that it was not until 1956, one year after the discovery of the antiproton, that scientists at the Bevatron in Berkeley observed the first antineutron.

3.6 The Pi Meson (π)

Sometimes in physics there is a theorist with the insight to see that an unexplained phenomenon can be understood in terms of a new particle, and he can stimulate the world of experimental physics into a search for this particle. Such a man was Hideki Yukawa, in 1935 a lecturer in physics at Kyoto University in Japan. The problem he studied was one mentioned above: what holds the atomic nucleus together. The protons, being positively charged, should push each other apart immediately, and there seemed to be nothing to prevent the neutrons from simply drifting apart, since they carry no electric charge and since the gravitational force is so weak as to be negligible within a single nucleus. His solution was that there must be another force, peculiar to nuclei, a force that could only be observed in events on the nuclear scale. Such a force would have to have a very short range, perhaps 2×10^{-13} cm, about the diameter of a nuclear particle, but it would have to be very strong to overcome the electric forces in the nucleus. Further experimentation

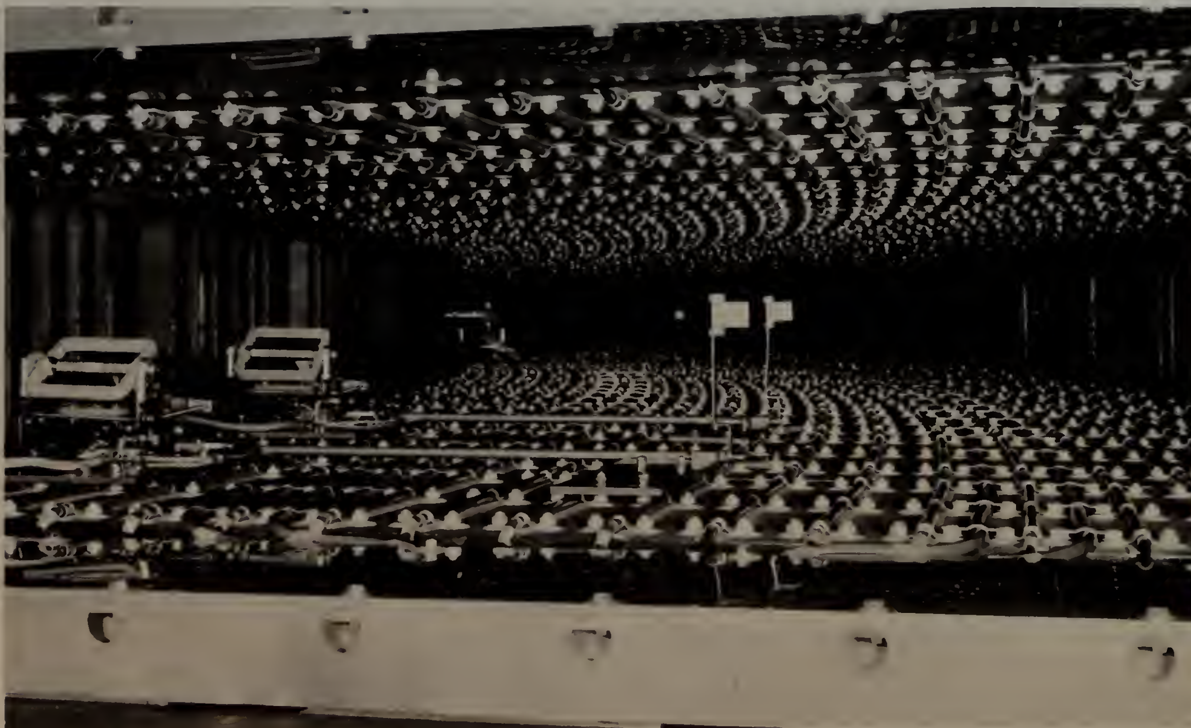


Fig. 3.9 View inside the aperture of the Bevatron showing targets (center) which are flipped up into the beam when desired. When the beam collides with a target, antiprotons, among other particles, are produced.

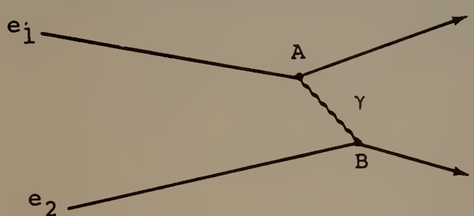
Fig. 3.10 Hideki Yukawa (right) and Niels Bohr (left) with two other physicists, inspecting experiments at Johns Hopkins University in 1959.

has convinced scientists that there is a force which possesses these special characteristics. We now call this force the "strong interaction."

The strong interaction takes place by means of particles called the pi mesons. To understand how this works, we will first return to a more familiar process: the electromagnetic interaction between two charged bodies. You know that a charged object has an electromagnetic field associated with it, and that this field can produce a force on another charged object. You also know that the emission of electromagnetic energy by an atom is best described as the emission of a photon with a specified frequency and energy. Likewise, the absorption of electromagnetic energy by an electron, as in the Compton effect or the photoelectric effect, can be described as the absorption of a photon. How are the field and the photon points of view connected? We make the connection by thinking of the electromagnetic field itself as being composed of a large number of photons. These photons have been emitted by the charged object producing the field, and the action of the field on another charged body can be described in terms of the absorption of photons from the field by that body. Since photons are the particles which carry the electromagnetic field from one place to another we say that the photons are the quanta of that field. Photons do not have a conserved family number, so they can be created and destroyed singly in such a process.

Recall that the quanta of any field are the particles whose quantum mechanical waves form the field. These quanta carry definite energy, momentum, and any other physical properties of the field.

The interaction of two electrons by the electromagnetic force can be illustrated by the following diagram.



Electron e_1 proceeds to A, where it emits a photon and heads off in a different direction in order to conserve momentum. The photon γ proceeds to B, where it is absorbed by electron e_2 and causes e_2 to be deflected. We could say that the two electrons repel each other by the electromagnetic (Coulomb) force, but another way to describe the event is to say that a photon is exchanged between the electrons and that this exchange causes the observed deflection. This latter way of speaking is preferred in particle physics, because it describes the "repulsion" between electrons in terms of simple and well-understood processes: emission of a photon by a charged particle at one point, travel of that photon through space, and absorption of the photon by another charged particle at another point. The electro-

magnetic attraction between two particles of opposite charge also takes place via the mechanism of photon exchange.

In a similar way, the interaction between two nucleons (that is, protons or neutrons) can be described in terms of the exchange of the particle which is the quantum of the strong interaction field, just as the photon is the quantum of the electromagnetic field. This was Yukawa's proposition. He derived the equations describing the motion of this new particle and estimated that it would have a mass of about 100 MeV. Of course it takes at least 100 MeV of energy to produce a particle of this mass, and such energies were in those days available only in cosmic rays. The experiments were difficult, but in 1947 C. F. Powell and his collaborators in Bristol, England, made the first cosmic ray observations of the expected particles, which are now called pi mesons. One year later, with the new Berkeley frequency-modulated cyclotron, it became possible to produce them at will in the laboratory.

The uncertainty principle was discussed in Unit 5, Section 20.5, where it was pointed out that the wave nature of matter made it impossible to measure the momentum and the position of a particle simultaneously to an accuracy any better than that allowed by the relation

$$\Delta P \, \Delta X \geq h/2\pi$$

where Δp is the uncertainty in the momentum, Δx the uncertainty in position, and h is Planck's constant. This principle also applies to simultaneous measurement of the energy and the time, according to the relation

$$\Delta E \Delta t \geq h/2\pi$$

where ΔE is the uncertainty in energy and Δt is the uncertainty in time, or otherwise stated, the length of time it takes to make the measurement of the energy.

$$\Delta E = \frac{h}{2\pi\Delta t}$$

$$\frac{h}{2\pi} = 6.6 \times 10^{-22} \text{ MeV sec}$$

$$\Delta t = 0.7 \times 10^{-23} \text{ sec}$$

$$\Delta E = \frac{6.6 \times 10^{-22}}{0.7 \times 10^{-23}}$$

$$= 100 \text{ MeV}$$

There is an interesting but rough argument based on the uncertainty principle, which allows an estimate of the mass of the mesons carrying the strong force between two nucleons. The range of this force is known to be about 2×10^{-13} cm, so even if a meson travels at the velocity of light, it will take at least 0.7×10^{-23} sec for it to travel from one nucleon to another with which it is interacting. During this time the energy of the system presumably must increase by at least the mass of the meson, apparently violating the law of conservation of energy. However this law only applies to experimentally measurable values of the energy, and according to the uncertainty principle, during the short time the meson is in flight we can only measure the energy of the system to an accuracy of $\Delta E = h/2\pi\Delta t = 100$ MeV. Then, if the mass of the meson was less than about 100 MeV, the apparent violation of conservation of energy in the meson exchange process would not be experimentally detectable. On the other hand, we do not expect the mass of the meson to be much below 100 MeV, because that would allow it to travel for a longer time and thus to a greater range without an observable violation of energy conservation. The known range of the nuclear force speaks against this possibility. Thus we expect the mass to be about 100 MeV, a value which agrees with Yukawa's prediction, although Yukawa's argument was somewhat different from that presented above.

Later study has shown that pi mesons occur in three charge states: 1, −1, and 0 in terms of the fundamental charge. Thus the strong interaction between nucleons can proceed by exchange of any of these particles, as long as it does so in a manner consistent with conservation of charge. This leads us to an important characteristic of the strong interaction: its independence of charge. Neutrons and protons, which differ only in charge, do not differ at

all insofar as strong interactions are concerned, and the strong force between two neutrons or a neutron and a proton is the same as that between two protons. Since the electromagnetic force is much weaker than the strong force, the effect of electric charge on the interaction of two nucleons can be included as a small correction after the (charge-independent) effects of the strong force are calculated. It is thought that the difference in mass of 0.14% between the neutron and the proton is due to the difference in their electric charges, while the rest of their mass difference is a result of their strong interactions.

3.7 The Muon

In the study of cosmic rays by several different laboratories in the early and mid-1930's, some particles were observed which were much more penetrating than others; these were called the "hard" component of cosmic rays. At first it was not known whether these particles were simply protons and electrons of exceedingly high energies or whether they were a new type of particle, but measurements made at California Institute of Technology in 1937 made it evident that a new particle had been discovered. This particle which we now call a muon (μ) could best be described as a heavy electron, since it is similar to the electron in all respects except mass, and that is about 200 times the electron mass. At first it seemed that this might be the particle postulated by Yukawa to account for nuclear forces, but it was observed that the new particles interacted much too rarely with nuclei for that identification to be correct. In fact, even today we know very little more about the muon than that it is a "heavy electron."

The muon was the first elementary particle that was experimentally observed to decay in the free state. It was suspected theoretically that free neutrons could undergo beta decay in the reaction neutron decays to proton, electron, and antineutrino:

$$n^0 \longrightarrow p^+ + e^- + \bar{\nu}_e$$

but this was not actually observed until 1950. Muons, on the other hand, not only decayed themselves, but were also produced in the radioactive decay of another particle, the pi meson. The equations follow, and Fig. 3.11 shows several "pi-mu-e" decays in a bubble chamber.

$$\pi^+ \longrightarrow \mu^+ + \nu_\mu$$
$$\mu^+ \longrightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

Thus a pi plus decays into a mu plus and a neutrino. Then the mu plus decays into a positron, a neutrino, and an antineutrino. Notice that electric charge is conserved, since it is +1 at each stage of the decay chain. A similar series of decays starts with a pi minus meson.

Fig. 3.11 The life of three muons is recorded in three short tracks produced in the liquid hydrogen of a bubble chamber.

The fact that there are two kinds of neutrino, ν_e and ν_μ, was not discovered experimentally until 1962. However, we have included these designations here to allow us to talk about conservation of electron family number and muon family number. A table of these properties is presented here for convenience. Using the table we can examine the conservation of these numbers in the pi-mu-e decay chain.

TABLE 3.2 THE ELECTRON AND MUON FAMILIES

Name	*Symbol*	*Electron Family Number*	*Muon Family Number*
Electron	e^-	+1	0
Electron's neutrino	ν_e	+1	0
Positron	e^+	−1	0
Electron's antineutrino	$\bar{\nu}_e$	−1	0
Mu minus	μ^-	0	+1
Muon's neutrino	ν_μ	0	+1
Mu plus	μ^+	0	−1
Muon's antineutrino	$\bar{\nu}_\mu$	0	−1
All other particles		0	0

Consider the decay of a pi meson, using this table.

	$\pi^+ \longrightarrow$	μ^+	$+\ \bar{\nu}_\mu$
electron family number	0	0	0
total electron family number	0	0	
muon family number	0	−1	+1
total muon family number	0	0	

Next, consider the decay of the muon.

	$\mu^+ \longrightarrow$	e^+	$+\ \nu_e$	$+\ \bar{\nu}_\mu$
electron family number	0	−1	+1	0
total electron family number	0		0	
muon family number	−1	0	0	−1
total muon family number	−1		−1	

Thus we see that electron family number and muon family number are conserved in these decays, as indeed they are in all interactions.

3.8 The Simplicity of 1947

Although the list of known particles grew appreciably between 1932 and 1947, this growth did not necessarily make the physics more complicated. As we have seen, it brought with it explanations for the three vexing problems we mentioned in Section 3.1. Nuclear forces could be understood in terms of the exchange of pi mesons; the details of beta decay were explained by the neutrino hypothesis;

and the discovery of the positron led to an acceptable interpretation of the Dirac theory of the electron. The particles that were well-established experimentally or theoretically by 1947 are listed in Table 3.3. It is interesting to compare this with the earlier list in Table 3.1.

TABLE 3.3 LIST OF PARTICLES KNOWN IN 1947

Particle	*Symbol*	*Charge*	*Mass (MeV)*
Photon	γ	0	0
Neutrino	ν	0	0
Antineutrino	$\bar{\nu}$	0	0
Electron	e^-	−1	0.5
Positron	e^+	+1	0.5
Muon	μ^-	−1	106
Antimuon	μ^+	+1	106
Pi meson	π^+	+1	140
	π^0	0	135
	π^-	−1	140
Proton	p^+	+1	938
Antiproton	$\bar{p}^-$	−1	938
Neutron	n^0	0	940
Antineutron	$\bar{n}^0$	0	940

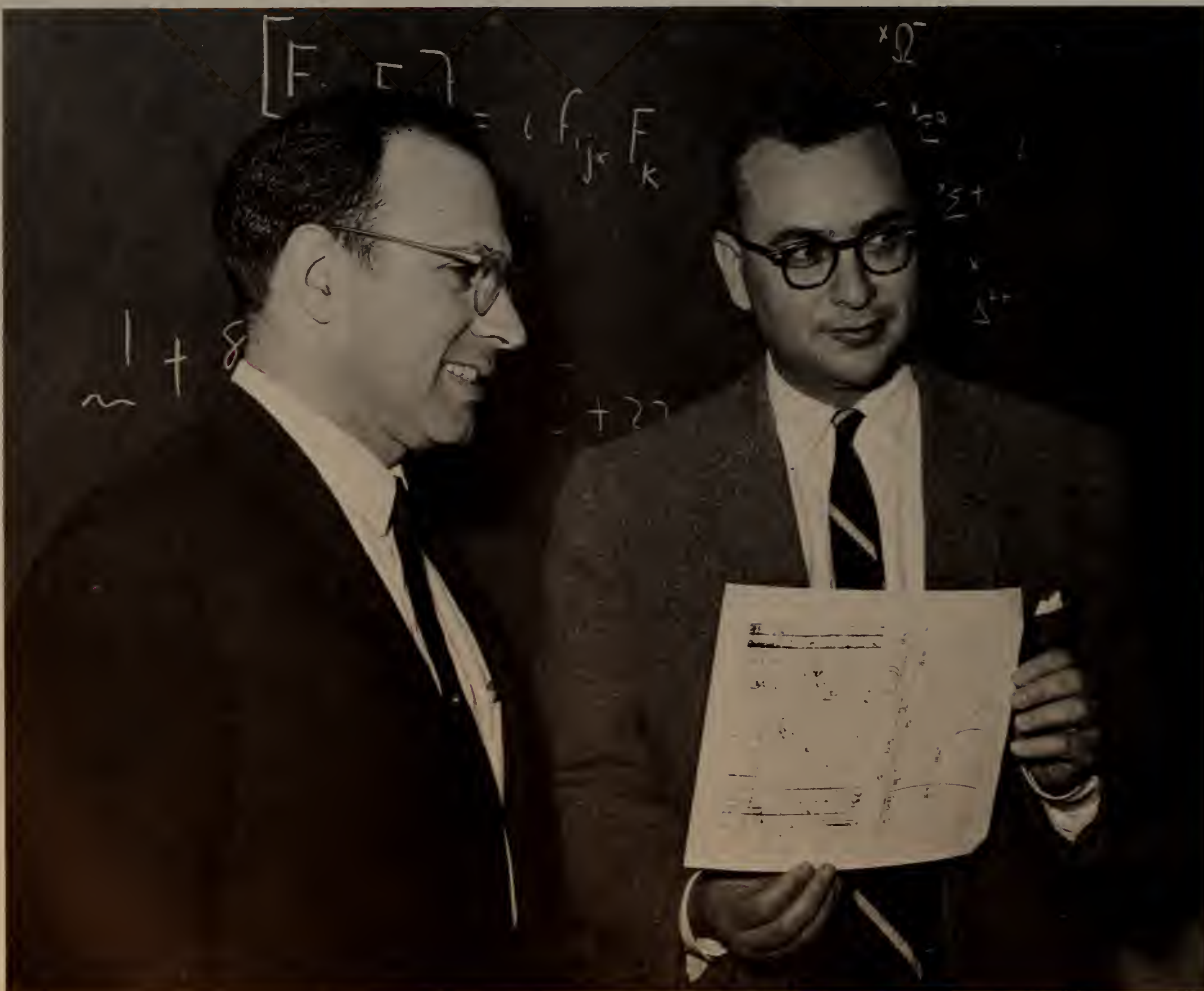
In 1947 this table showed every evidence of being complete. In fact, if anything, it was too complete because of the muon, which apparently served no useful purpose. A few of the particles on this list had not yet been observed experimentally, but this was not worrisome as their existence was well-established on theoretical grounds. In fact there was reasonable hope of explaining the entire microscopic behavior of matter on the basis of only the particles known at that time.

Q1 For each of the particles in Table 3.3 describe its function in terms of its interactions and in terms of the atomic model of matter.

Q2 For each of the tracks in Fig. 3.11 identify the particle and its direction of travel.

Q3 In Fig. 3.11 which particles are travelling fastest? How do you know?

Q4 Discuss what could happen if a low-energy antiproton collides with a proton. Use your knowledge of the conservation laws.



Dr. Yuval Ne'eman (left) and Dr. Murray Gell-Mann who independently proposed the "Eightfold Way."

CHAPTER FOUR

CHAOS ENTERS AND CHAOS RESOLVED

4.1 Chaos Enters

The hope that the list of particles would remain brief and simple was short-lived. In 1947, the same year that our list was "completed" by the discovery of the pi meson, careful study of cosmic ray pictures revealed the presence of strange new particles. It would have astonished their discoverers, G. D. Rochester and C. C. Butler of Manchester, England, to know that their two new particles were but the forerunners of over two hundred that would be discovered in the next twenty years! Indeed, even now, there is every indication that there are many more to come. Let us examine briefly some of the ways in which physicists hope to make sense of this apparently chaotic situation.

4.2 Strangeness

One of the most peculiar properties of the newly-discovered particles was that they decayed rather slowly, despite the fact that the decay products are particles subject to the strong interaction. The previously-known unstable particles also decayed rather slowly, but this was not surprising because their decay products always include some particles that are not subject to the strong interaction. The new particles are readily produced in high-energy collisions, for example pi minus and proton go to kay zero and lambda zero:

$$\pi^- + p^+ \longrightarrow K^0 + \Lambda^0$$

and they decay by such processes as lambda zero goes to proton and pi minus:

$$\Lambda^0 \longrightarrow p^+ + \pi^-$$

Production takes place in 10^{-23} sec, a time characteristic of the strong interaction, but decay takes a much longer time, 10^{-10} sec, typical of the weak interaction. This suggests that something is suppressing the strong interaction in the decay process, leaving only

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EVIDENCE FOR THE EXISTENCE OF NEW UNSTABLE ELEMENTARY PARTICLES

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AMONG some fifty counter-controlled cloud-chamber photographs of penetrating showers which we have obtained during the past year as part of an investigation of the nature of penetrating particles occurring in cosmic ray showers under lead, there are two photographs containing forked tracks of a very striking character. These photographs have been selected from five thousand photographs taken in an effective time of operation of 1,500 hours. On the basis of the analysis given below we believe that one of the forked tracks, shown in Fig. 1 (tracks a and b), represents the spontaneous transformation in the gas of the chamber of a new type of uncharged elementary particle into lighter charged particles, and that the other, shown in Fig. 2 (tracks a and b), represents similarly the transformation of a new type of charged particle into two light particles, one of which is charged and the other uncharged.

The experimental data for the two forks are given in Table 1; H is the value of the magnetic field, α the angle between the tracks, p and Δp the measured momentum and the estimated error. The signs of the particles are given in the last column of the table, a plus sign indicating that the particle is positive if moving down in the chamber. Careful re-projection of the stereoscopic photographs has shown that each pair of tracks is copunctal. Moreover, both tracks occur in the middle of the chamber in a region of uniform illumination, the presence of background fog surrounding the tracks indicating good condensation conditions.

Though the two forks differ in many important respects, they have at least two essential features in common: first, each consists of a two-pronged fork with the apex in the gas; and secondly, in neither case is there any sign of a track due to a third ionizing particle. Further, very few events at all similar to these forks have been observed in the 3-cm. lead plate, whereas if the forks were due to any type of collision process one would have expected several hundred times as many as in the gas. This argument indicates, therefore, that the tracks cannot be due to a collision process but must be due to some type of spontaneous process for which the probability depends on the distance travelled and not on the amount of matter traversed.

TABLE 1. EXPERIMENTAL DATA

Photograph	H (gauss)	α (deg.)	Track	p (eV./c.)	Δp (eV./c.)	Sign
1	3500	66·6	a b	$3{\cdot}4 \times 10^8$ $3{\cdot}5 \times 10^8$	$1{\cdot}0 \times 10^8$ $1{\cdot}5 \times 10^8$	+ −
2	7200	161·1	a b	$6{\cdot}0 \times 10^8$ $7{\cdot}7 \times 10^8$	$3{\cdot}0 \times 10^8$ $1{\cdot}0 \times 10^8$	+ +

This conclusion can be supported by detailed arguments. For example, if either forked track were due to the deflexion of a charged particle by collision with a nucleus, the transfer of momentum would be so large as to produce an easily visible recoil track. Then, again, the attempt to account for Fig. 2 by a collision process meets with the difficulty that the incident particle is deflected through 19° in a single collision in the gas and only 2·4° in traversing 3 cm. of lead—a most unlikely event. One specific collision process, that of electron pair production by a high-energy photon in the field of the nucleus, can be excluded on two grounds: the observed angle between the tracks would only be a fraction of a degree, for example, 0·1° for Fig. 1, and a large amount of electronic component should have accompanied the photon, as in each case a lead plate is close above the fork.

We conclude, therefore, that the two forked tracks do not represent collision processes, but do represent spontaneous transformations. They represent a type of process with which we are already familiar in the decay of the meson into an electron and an assumed neutrino, and the presumed decay of the heavy meson recently discovered by Lattes, Occhialini and Powell[1].

We shall now discuss possible alternative explanations of the two forks.

Photograph 1. We must examine the alternative possibility of Photograph 1 representing the spontaneous disintegration of a charged particle, coming up from below the chamber, into a charged and an uncharged particle. If we apply the argument which led to equation (4) to this process, it is readily seen that the incident particle would have a minimum mass of $1{,}280m$. Thus the photograph cannot be explained by the decay of a back-scattered ordinary meson. Bearing in mind the general direction of the other particles in the shower, it is thought that assumption of the disintegration of a neutral particle moving downwards into a pair of particles of about equal mass is more probable. Further, it can be stated with some confidence that the observed ionizing particles are unlikely to be protons because the ionization of a proton of momentum $3{\cdot}5 \times 10^8$ eV./c. would be more than four times the observed ionization.

Photograph 2. In this case we must examine the possibility of the photograph representing the spontaneous decay of a neutral particle coming from the right-hand side of the chamber into two charged particles. The result of applying equation (4) to this process is to show that the minimum mass of the neutral particle would be about $3{,}000m$. In view of the fact that the direction of the neutral particle would have to be very different from the direction of the main part of the shower, it is thought that the original assumption of the decay of a charged particle into a charged penetrating particle and an assumed neutral particle is the more probable.

We conclude from all the evidence that Photograph 1 represents the decay of a neutral particle, the mass of which is unlikely to be less than $770m$ or greater than $1{,}600m$, into the two observed charged particles. Similarly, Photograph 2 represents the disintegration of a charged particle of mass greater than $980m$ and less than that of a proton into an observed penetrating particle and a neutral particle. It may be noted that no neutral particle of mass $1{,}000m$ has yet been observed; a charged particle of mass $990m \pm 12$ per cent has, however, been observed by Leprince-Ringuet and L'héritier[2].

Peculiar cloud-chamber photographs taken by Jánossy, Rochester and Broadbent[3] and by Daudin[4] may be other examples of Photograph 2.

It is a pleasure to record our thanks to Prof. P. M. S. Blackett for the keen interest he has taken in this investigation and for the benefit of numerous stimulating discussions. We also wish to acknowledge the help given us by Prof. L. Rosenfeld, Mr. J. Hamilton and Mr. H. Y. Tzu of the Department of Theoretical Physics, University of Manchester. We are indebted to Mr. S. K. Runcorn for his assistance in running the cloud chamber in the early stages of the work.

[1] Lattes, C. M. G., Occhialini, G. P. S., and Powell, C. F., *Nature*, **160**, 453, 486 (1947).
[2] Leprince-Ringuet, L., and L'héritier, M., *J. Phys. Radium.* (Sér. 8), 7, 66, 69 (1946). Bethe, H. A., *Phys. Rev.*, **70**, 821 (1946).
[3] Jánossy, L., Rochester, G. D., and Broadbent, D., *Nature*, 155,1 42 (1945). (Fig. 2. Track at lower left-hand side of the photograph.)
[4] Daudin, J., *Annales de Physique*, 11e Série, **19** (Avril-Juin), 1944 (Planche IV, Cliché 16).

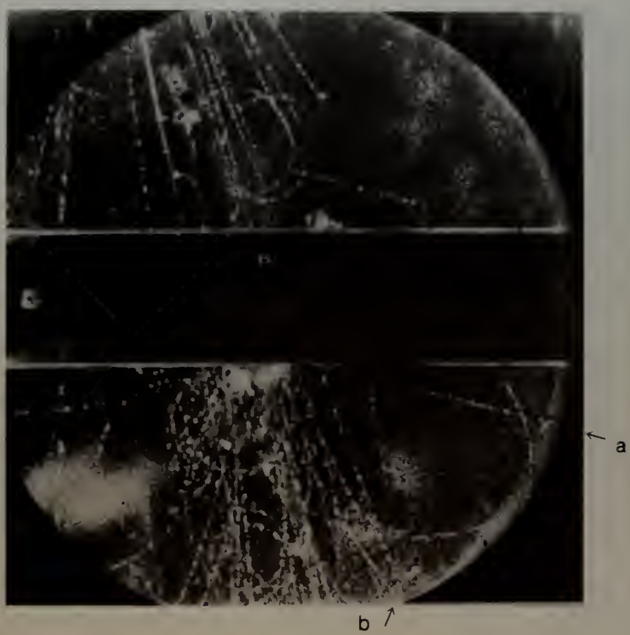


Fig. 1. Photograph showing an unusual fork (a, b) in the gas. The direction of the magnetic field is such that a positive particle coming downwards is deviated in an anticlockwise direction.

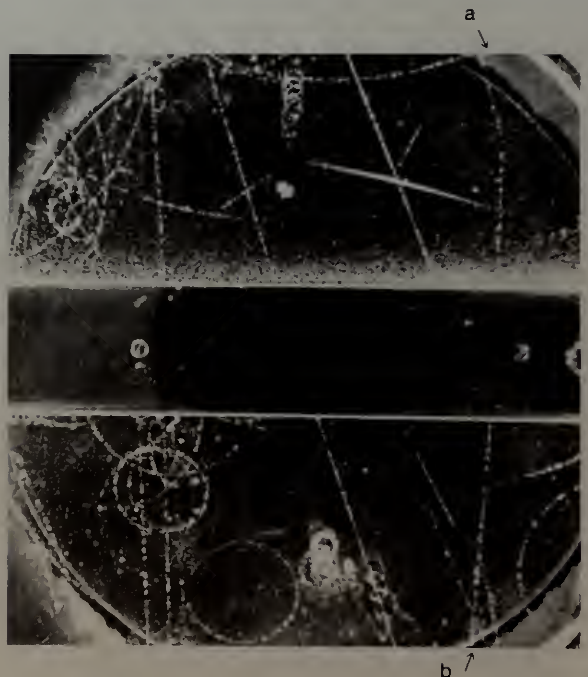


Fig. 2. Photograph showing an unusual fork (a, b). The direction of the magnetic field is such that a positive particle coming downwards is deviated in a clockwise direction.

Fig. 1 and 2 are reproduced from *Cloud Chamber Photographs of the Cosmic Radiation* by G. D. Rochester and J. G. Wilson, Academic Press, Inc. New York, 1952.

the weak interaction to cause it. Although decay via the electromagnetic interaction would lead to different products, it would also be expected to proceed at a greater rate than decay via the weak interaction. Since it is not generally observed for these new particles, something must be suppressing electromagnetic decays also.

Murray Gell-Mann in the United States and Kazuhiko Nishijima in Japan independently proposed in 1953 that elementary particles had a new property that could be described in terms of a quantum number which we now call *strangeness*. In section 2.6 of this unit we observed the bubble chamber tracks of strange particles and discussed the concept of strangeness. You may recall that there is a law of conservation of strangeness, but that unlike the other conservation laws we have been studying, it only holds some of the time. Specifically, reactions that proceed via the weak interaction do not obey the law of conservation of strangeness. Nevertheless, strangeness is a very useful concept in dealing with reactions that proceed via the strong or electromagnetic interactions, for which the law of conservation of strangeness must hold.

Strangeness is gradually being replaced by a related quantity, the hypercharge Y, which equals the strangeness plus the baryon number. Hypercharge is conserved in exactly the same situations as strangeness, as it must be, since baryon number is always conserved.

The production reaction ($\pi^- + p^+ \longrightarrow \Lambda^0 + K^0$) above can proceed rapidly, via the strong interaction, because strangeness is conserved.

The decay reaction ($\Lambda^0 \longrightarrow p^+ + \pi^-$) can only go slowly, via the weak interaction, because strangeness is not conserved, although all other relevant conservation laws are obeyed. The strangeness balance in these reactions is indicated below:

Strange particle production

	π^-	$+\ p^+ \longrightarrow$	K^0	$+\ \Lambda^0$
strangeness	0	0	+1	−1
total strangeness (conserved)	0		0	

Strange particle decay

	$\Lambda^0 \longrightarrow$	p^+	$+\ \pi^-$
strangeness	−1	0	0
total strangeness (not conserved)	−1	0	

4.3 Chaos Increases

Resonances. Not all particles have a decay scheme which violates the conservation of strangeness and therefore cannot proceed via the strong interactions; there are a great many for which both production and decay conserve strangeness and proceed in times typical of the strong interaction. Since the average lifetime of such a particle is only 10^{-23} sec, it is necessary to use indirect means to observe it. These short-lived particles are sometimes called "resonances," a name which is used to distinguish them from their longer-lived brothers. The great majority of particles on our present list are in fact resonances, although resonances are less important in ordinary matter than the more stable particles.

The first resonance, "sigma star" (Σ^*) was observed in 1960 by the bubble chamber group under the direction of Luis W. Alvarez at the University of California at Berkeley. A typical event is shown in Fig. 4.1. The reaction is kay minus and proton go to sigma star plus and pi minus, followed immediately by sigma star plus decays to lambda zero and pi zero, as indicated in the following equations:

Resonance production

	K^-	$+\ p^+ \longrightarrow$	Σ^{*+}	$+\ \pi^-$
strangeness	−1	0	−1	0
total strangeness (conserved)	−1		−1	

Resonance decay

	$\Sigma^{*+} \longrightarrow$	Λ^0	$+\ \pi^+$
strangeness	−1	−1	0
total strangeness (conserved)	−1	−1	

The total strangeness adds up to −1 on both sides of these two reactions; thus they proceed by the strong interaction, and the Σ^{*+}

Fig. 4.1 A Σ^{*+} resonance particle and a π^- meson are produced in a bubble chamber collision between a K^- meson and a proton at O. The resonance particle disintegrates before it can leave a track, into a Λ^0 and a π^+ particle. The neutral Λ^0 leaves no track, but its decay into a π^- and a proton can be seen downstream.

decays much more rapidly than the particles like the Λ^0 discussed above which do not conserve strangeness in their decay. Notice in the picture that the Σ^* has decayed into Λ^0 and π^+ almost immediately upon production but that the Λ^0 produced as a result of this decay travels a measurable distance before decaying into a proton and a pi minus meson.

4.4 The Situation Now

The discovery of new particles and resonances continued at a rapid pace, as one can see from the size of the 1970 list presented in Table 4.1. The particles are listed in order of increasing mass. Particles that have approximately the same mass and that are closely related in other ways are listed as a group, or *multiplet*. As we shall see later, the concept of multiplets has helped physicists to simplify greatly the classification of particles.

TABLE 4.1 LIST OF PARTICLES IN 1970

Mass of Multiplet (MeV)	*Particles in Multiplet*	*Mass of Multiplet (MeV)*	*Particles in Multiplet*
0	γ	1540	$F1^{+}\ F1^{0}\ F1^{-}$ (*)
0	$\nu_e\ \bar{\nu}_e$	1640	$\pi_A^{+}\ \pi_A^{0}\ \pi_A^{-}$ (*)
0	$\nu_\mu\ \bar{\nu}_\mu$	1650	$\Delta^{*++}\ \Delta^{*+}\ \Delta^{*0}\ \Delta^{*-}\ \bar{\Delta}^{*--}\ \bar{\Delta}^{*-}\ \bar{\Delta}^{*0}\ \bar{\Delta}^{*+}$
0.5	$e^{-}\ e^{+}$	1670	$\Sigma^{*+}\ \Sigma^{*0}\ \Sigma^{*-}\ \bar{\Sigma}^{*-}\ \bar{\Sigma}^{*0}\ \bar{\Sigma}^{*+}$
106	$\mu^{-}\ \mu^{+}$	1670	$\Lambda^{*0}\ \bar{\Lambda}^{*0}$
138	$\pi^{+}\ \pi^{0}\ \pi^{-}$	1670	$N^{*+}\ N^{*0}\ \bar{N}^{*0}\ \bar{N}^{*-}$
496	$K^{+}\ K^{0}\ \bar{K}^{0}\ \bar{K}^{-}$	1670	$\Delta^{*++}\ \Delta^{*+}\ \Delta^{*0}\ \Delta^{*-}\ \bar{\Delta}^{*--}\ \bar{\Delta}^{*-}\ \bar{\Delta}^{*0}\ \bar{\Delta}^{*+}$
549	η^{0}	1670	$\rho_N^{+}\ \rho_N^{0}\ \rho_N^{-}$ (*)
700	ϵ^{0}	1672	$\Omega^{-}\ \bar{\Omega}^{+}$
765	$\rho^{+}\ \rho^{0}\ \rho^{-}$ (*)	1688	$N^{*+}\ N^{*0}\ \bar{N}^{*0}\ \bar{N}^{*+}$
784	ω^{0} (*)	1690	$\Delta^{*0}\ \bar{\Delta}^{*0}$
892	$K^{*+}\ K^{*0}\ \bar{K}^{*0}\ \bar{K}^{*-}$	1700	$N^{*+}\ N^{*0}\ \bar{N}^{*0}\ \bar{N}^{*-}$
939	$p^{+}\ n^{0}\ \bar{p}^{0}\ \bar{n}^{+}$	1750	$\Sigma^{*+}\ \Sigma^{*0}\ \Sigma^{*-}\ \bar{\Sigma}^{*-}\ \bar{\Sigma}^{*0}\ \bar{\Sigma}^{*+}$
958	η'^{0} (*)	1765	$\Sigma^{*+}\ \Sigma^{*0}\ \Sigma^{*-}\ \bar{\Sigma}^{*-}\ \bar{\Sigma}^{*0}\ \bar{\Sigma}^{*+}$
966	$\delta^{+}\ \delta^{0}\ \delta^{-}$ (*)	1775	$K_A^{+}\ K_A^{0}\ \bar{K}_A^{0}\ \bar{K}_A^{-}$ (*)
1016	$\pi_N^{+}\ \pi_N^{0}\ \pi_N^{-}$ (*)	1815	$\Lambda^{*0}\ \bar{\Lambda}^{*0}$
1019	ϕ^{0} (*)	1820	$\Xi^{*-}\ \Xi^{*0}\ \bar{\Xi}^{*0}\ \bar{\Xi}^{*+}$
1060	η (*)	1830	$\Lambda^{*0}\ \bar{\Lambda}^{*0}$
1070	$A1^{+}\ A1^{0}\ A1^{-}$ (*)	1860	$N^{*+}\ N^{*0}\ \bar{N}^{*0}\ \bar{N}^{*-}$
1116	$\Lambda^{0}\ \bar{\Lambda}^{0}$	1890	$\Delta^{*++}\ \Delta^{*+}\ \Delta^{*0}\ \Delta^{*-}\ \bar{\Delta}^{*--}\ \bar{\Delta}^{*-}\ \bar{\Delta}^{*0}\ \bar{\Delta}^{*+}$
1193	$\Sigma^{+}\ \Sigma^{0}\ \Sigma^{-}\ \bar{\Sigma}^{-}\ \bar{\Sigma}^{0}\ \bar{\Sigma}^{+}$	1910	$\Delta^{*++}\ \Delta^{*+}\ \Delta^{*0}\ \Delta^{*-}\ \bar{\Delta}^{*--}\ \bar{\Delta}^{*-}\ \bar{\Delta}^{*0}\ \bar{\Delta}^{*+}$
1235	$B^{+}\ B^{0}\ B^{-}$ (*)	1910	$\Sigma^{*+}\ \Sigma^{*0}\ \Sigma^{*-}\ \bar{\Sigma}^{*-}\ \bar{\Sigma}^{*0}\ \bar{\Sigma}^{*+}$
1236	$\Delta^{++}\ \Delta^{+}\ \Delta^{0}\ \Delta^{-}\ \bar{\Delta}^{--}\ \bar{\Delta}^{-}\ \bar{\Delta}^{0}\ \bar{\Delta}^{+}$ (*)	1930	$\Xi^{*-}\ \Xi^{*0}\ \bar{\Xi}^{*+}\ \bar{\Xi}^{*0}$
1240-1400	$Q^{+}\ Q^{0}\ \bar{Q}^{0}\ \bar{Q}^{-}$ (*)	1950	$\Delta^{*++}\ \Delta^{*+}\ \Delta^{*0}\ \Delta^{*-}\ \bar{\Delta}^{*--}\ \bar{\Delta}^{*-}\ \bar{\Delta}^{*0}\ \bar{\Delta}^{*+}$
1260	f^{0} (*)	1990	$N^{*+}\ N^{*0}\ \bar{N}^{*0}\ \bar{N}^{*-}$
1285	D^{0} (*)	2030	$\Sigma^{*+}\ \Sigma^{*0}\ \Sigma^{*-}\ \bar{\Sigma}^{*-}\ \bar{\Sigma}^{*0}\ \bar{\Sigma}^{*+}$
1300	$A2^{+}\ A2^{0}\ A2^{-}$ (*)	2040	$N^{*+}\ N^{*0}\ \bar{N}^{*0}\ \bar{N}^{*-}$
1318	$\Xi^{-}\ \Xi^{0}\ \bar{\Xi}^{0}\ \bar{\Xi}^{+}$	2100	$\Lambda^{*0}\ \bar{\Lambda}^{*0}$
1385	$\Sigma^{*+}\ \Sigma^{*0}\ \Sigma^{*-}\ \bar{\Sigma}^{*-}\ \bar{\Sigma}^{*0}\ \bar{\Sigma}^{*+}$	2190	$N^{*+}\ N^{*0}\ \bar{N}^{*0}\ \bar{N}^{*-}$
1405	$\Lambda^{*0}\ \bar{\Lambda}^{*0}$	2250	$\Sigma^{*+}\ \Sigma^{*0}\ \Sigma^{*-}\ \bar{\Sigma}^{*-}\ \bar{\Sigma}^{*0}\ \bar{\Sigma}^{*+}$
1420	$K_N^{+}\ K_N^{0}\ \bar{K}_N^{0}\ \bar{K}_N^{-}$ (*)	2350	$\Lambda^{*0}\ \bar{\Lambda}^{*0}$
1422	E^{0} (*)	2420	$\Delta^{*++}\ \Delta^{*+}\ \Delta^{*0}\ \Delta^{*-}\ \bar{\Delta}^{*--}\ \bar{\Delta}^{*-}\ \bar{\Delta}^{*0}\ \bar{\Delta}^{*+}$
1470	$N^{*+}\ N^{*0}\ \bar{N}^{*0}\ \bar{N}^{*-}$	2455	$\Sigma^{*+}\ \Sigma^{*0}\ \Sigma^{*-}\ \bar{\Sigma}^{*-}\ \bar{\Sigma}^{*0}\ \bar{\Sigma}^{*+}$
1514	f'^{0} (*)	2575	$\Sigma^{*+}\ \Sigma^{*0}\ \Sigma^{*-}\ \bar{\Sigma}^{*-}\ \bar{\Sigma}^{*0}\ \bar{\Sigma}^{*+}$
1520	$\Lambda^{*0}\ \bar{\Lambda}^{*0}$	2650	$N^{*+}\ N^{*0}\ \bar{N}^{*0}\ \bar{N}^{*-}$
1520	$N^{*+}\ N^{*0}\ \bar{N}^{*0}\ \bar{N}^{*-}$	2850	$\Delta^{*++}\ \Delta^{*+}\ \Delta^{*0}\ \Delta^{*-}\ \bar{\Delta}^{*--}\ \bar{\Delta}^{*-}\ \bar{\Delta}^{*0}\ \bar{\Delta}^{*+}$
1530	$\Xi^{*-}\ \Xi^{*0}\ \bar{\Xi}^{*0}\ \bar{\Xi}^{*+}$	3030	$N^{*+}\ N^{*0}\ \bar{N}^{*0}\ \bar{N}^{*-}$
1535	$N^{*+}\ N^{*0}\ \bar{N}^{*0}\ \bar{N}^{*-}$	3230	$\Delta^{*++}\ \Delta^{*+}\ \Delta^{*0}\ \Delta^{*-}\ \bar{\Delta}^{*--}\ \bar{\Delta}^{*-}\ \bar{\Delta}^{*0}\ \bar{\Delta}^{*+}$

Note: * indicates a resonance.

An up-to-date listing with complete details of the properties of these particles may be found in "Review of Particle Properties," published annually in the January edition of *Reviews of Modern Physics* by the Particle Data Group.

The notation for describing particles is yet to become fully standardized, but that used in Table 4.1 is still suggestive of various properties of the particles. The basic symbol indicates the name of the particle, as well as its family number and strangeness, according to a certain code that we need not discuss in detail. A super-

script ($^+$, ^{0}, or $^-$) indicates the charge in units of the fundamental charge. A bar over the symbol indicates an antiparticle, which has family number and strangeness which are the negatives of the values for the corresponding particle. A superscript star (*) indicates a resonance, a particle that has only a very transient existence since it decays via the strong interaction. If necessary, resonances can be distinguished from one another by writing the mass in parentheses after the symbol. Some resonances do not conventionally carry a star in their symbols, and in such cases we have added a star at the end of the group.

4.5 The Eightfold Way

As the list of particles grew, it presented an increasing challenge to the theorists. Could they find any order, any regularities among them?

One of the most fruitful proposals was made by Murray Gell-Mann, an American, and Yuval Ne'eman, an Israeli, in 1961. It was christened the "Eightfold Way", a phrase borrowed from Buddhist theology. As an example of how this theory works, let us consider the following eight particles:

TABLE 4.2 LIST OF BARYONS WITH SPIN ½ AND PARITY +

Name	*Symbol*	*Mass (MeV)*	*Strangeness*	*Charge*
Proton	p^+	938	0	1
Neutron	n^0	940	0	0
Lambda	Λ^0	1116	−1	0
Sigma plus	Σ^+	1189	−1	1
Sigma zero	Σ^0	1193	−1	0
Sigma minus	Σ^-	1197	−1	−1
Xi zero	Ξ^0	1315	−2	0
Xi minus	Ξ^-	1321	−2	−1

Although they differ from one another in charge and strangeness, these particles were selected from the long list of particles because only these share the following properties:

1. They are all baryons, with baryon number equal to 1.
2. They all have spin angular momentum of $\frac{1}{2}$.
3. They all have positive parity.
4. They are all stable against decay via the strong interaction.

Notice that the eight particles in this baryon octet occur in charge multiplets. For example, the neutron and proton form a charge doublet: they are the same except for their electric charge and a slight mass difference. We can take this into account by saying that the neutron and proton are just different charge states of a

single particle called the nucleon, and we could emphasize it by using the symbols N^0 and N^+ instead of n^0 and p^+, although it has not become conventional to do so. It is believed that the differences in mass among members of a charge multiplet can be completely explained on the basis of their differences in charge alone. The largest mass difference, 8 MeV, occurs for the different charge states of the sigma multiplet and this is less than 1% of the mass of the sigma particle. This procedure allows us to think of this octet in terms of just four different particles, occurring in various charge states. This idea is illustrated in the following list:

TABLE 4.3 LIST OF BARYON MULTIPLETS WITH SPIN ½ AND PARITY +

Name	*Symbol*	*Multiplicity*	*Average Mass* (MeV)	*Strangeness*
Nucleon	N	2	939	0
Lambda	Λ	1	1116	−1
Sigma	Σ	3	1193	−1
Xi	Ξ	2	1318	−2

This approach can be carried further: the four multiplets N, Λ, Σ, and Ξ can be thought of as forming another kind of multiplet, differing from one another only in strangeness and somewhat in mass. It is believed that these mass differences, which run about 100 MeV, or about 10% of the mass of these particles, can be completely explained on the basis of their differences in strangeness and multiplicity.

It is not surprising then to hear the original octet referred to as a supermultiplet, within which particles differ only in charge and strangeness, with the relatively small mass differences which these other differences cause.

Thus, the original list of eight has been reduced to a "list" with but a single entry!

TABLE 4.4 BARYON SUPERMULTIPLET WITH SPIN ½ AND PARITY +

Symbol	*Average Mass* (MeV)
Baryon $\frac{1}{2}^+$	1151

The idea which Gell-Mann and Ne'eman had was that the particles of this octet are not to be thought of as eight different kinds of particle, but as just one kind of particle: the baryon with spin ½ and positive parity. This baryon can be found in various charge

states and various strangeness states, but fundamentally it is still the same kind of particle. A chart (Fig. 4.2) shows its various states. Each state is indicated by the appropriate symbol. Σ^0 and Λ^0 have the same values of charge and strangeness.

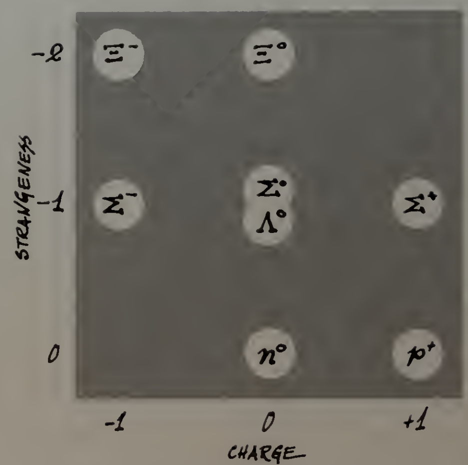


Fig. 4.2 States of the baryon with spin $\frac{1}{2}$, parity$^+$.

As an analogy, consider a set of fifteen billiard balls. They are alike in many respects, but they differ in color, pattern (striped or solid), and the number on the side. We could say that there is just one basic object: the billiard ball, but that it comes in various states of color, pattern, and number, just as there is one basic ½$^+$ baryon that comes in various states of charge, strangeness, and mass.

This classification of particles, which is relevant to their strong interactions, is based on the possibility that the strong force between two particles may not depend on the charge state or the strangeness state in which they happen to be, although other kinds of forces may depend on these quantities. To see what this means, we must realize that there are two aspects to the interactions between particles. First, there is the force between the particles, which may depend upon some of the internal properties of the particles as well as their relative position and velocity. Second, there are laws requiring that certain quantities be conserved during the reaction, although the force of interaction may or may not depend on these quantities. For example, the electromagnetic force between two protons depends on their charges, but the strong force between them does not. Nevertheless, total charge is conserved whenever the protons interact, no matter which force is involved.

Experimental results do show that the strong force is indeed independent of the charge of the particles involved, and that it is approximately independent of the strangeness. Therefore it has been speculated that the strong interaction may really be composed of two parts: a dominant "very strong" part that does not depend on strangeness, and a "medium strong" part that does. Neither part of the strong force depends on charge. So, at least from the point of view of the very strong interaction, there is just one baryon with spin $\frac{1}{2}$ and positive parity, although it can come with any of eight different combinations of charge and strangeness. As mentioned above, the fact that the very strong force does not depend on charge or strangeness does not alter the additional fact that in a strong interaction the products of the reaction must be consistent with conservation of these two quantities.

The Eightfold Way groups the strongly interacting particles into supermultiplets, which may contain 1, 8, or 10 particles. These are designated singlet, octet, and decuplet states respectively, and some of each have been found. This theory not only determines the size of the supermultiplets, but also specifies certain relationships

among the properties of the particles within a supermultiplet. Its most notable success has been in accurately predicting the mass differences among members of a supermultiplet, as we shall see below.

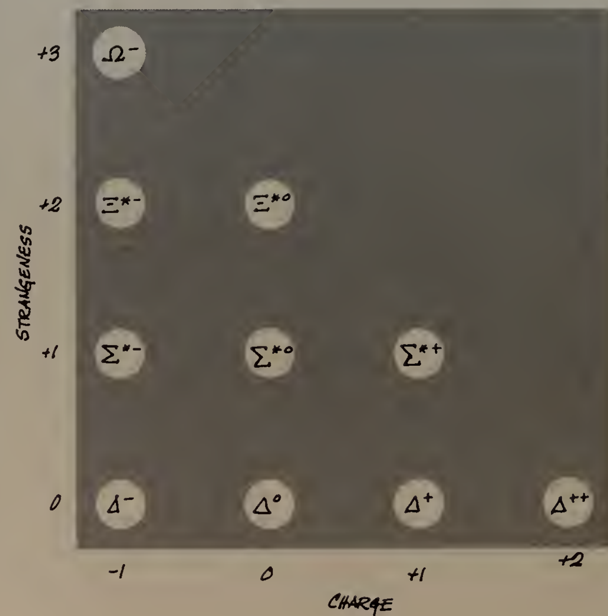


Fig. 4.3 States of the baryon with spin $\frac{3}{2}$ and parity$^+$ in 1961.

4.6 The Omega Minus Story

At the time it was proposed, the Eightfold Way was only one of several competing schemes for the classification of the elementary particles, and as usual it was up to the experimentalists to prove or disprove it. The evidence came in connection with the baryons of spin $\frac{3}{2}$ and positive parity. In 1961, seven of them were known:

TABLE 4.5 BARYONS WITH SPIN 3/2 AND PARITY +

Name	*Symbol*	*Mass (MeV)*	*Strangeness*	*Charge*
Delta double plus	Δ^{++}	1233	0	+2
Delta plus	Δ^{+}	1235	0	+1
Delta zero	Δ^{0}	1237	0	0
Delta minus	Δ^{-}	1239	0	−1
Sigma star plus	Σ^{*+}	1382	−1	+1
Sigma star zero	Σ^{*0}	1385	−1	0
Sigma star minus	Σ^{*-}	1388	−1	−1

According to the theory, this supermultiplet was not complete: it should be a decuplet, containing ten particles altogether. Figure 4.3 is a chart showing the strangeness and charge of the members of this decuplet. Known particles are represented by the appropriate symbols, while those that were predicted but which had not been observed are represented by open circles.

In 1962, experimenters reported the discovery of a pair of particles, xi star zero (Ξ^{*0}) and xi star minus (Ξ^{*-}) with strangeness −2 which nicely filled two of the holes in this baryon decuplet. This led to an intensive search for the final particle, the omega minus (Ω^-). If found, this particle would have spin $\frac{3}{2}$, positive parity, strangeness −3, and charge −1. The Eightfold Way predicted that the average masses of the different charge multiplets in a decuplet would be evenly spaced. Therefore the omega minus should have a mass of about 1677 MeV, as shown in the following list:

TABLE 4.6 BARYON MULTIPLETS WITH SPIN 3/2 AND PARITY+

Name	*Symbol*	*Average Mass* (MeV)	*Mass Difference*
Delta	Δ	1236	
			149
Sigma star	Σ^*	1385	
			145
Xi star	Ξ^*	1530	
			(Use 147, the average of the above)
Omega minus	Ω^-	(1677 predicted)	

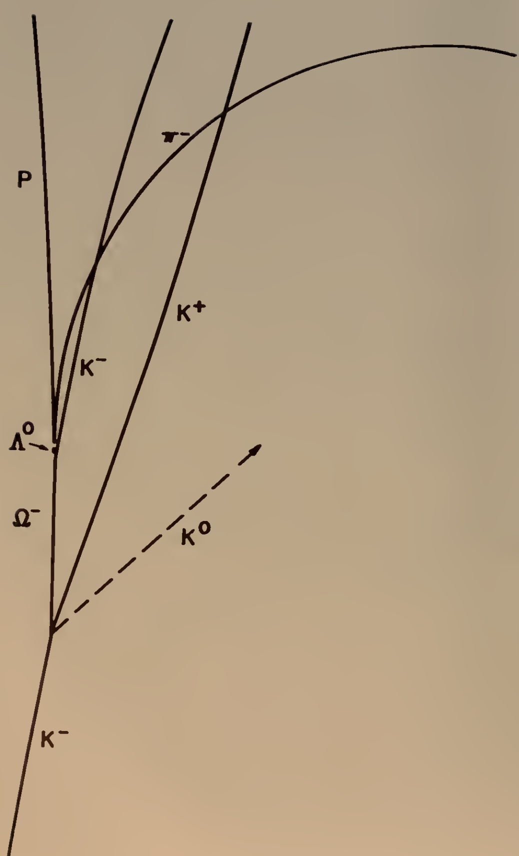
The search for the omega minus was carried out at the largest accelerators in the world—CERN in Geneva and Brookhaven National Laboratory in New York. On January 31, 1963, the first Ω^- particle was found by the Brookhaven group, using the 80-inch hydrogen bubble chamber exposed to a K^- beam at 5 GeV. Since then several more of these elusive particles have been found, confirming the original discovery. The bubble chamber track of one of these Ω^- particles is shown in Fig. 4.4 on the next page. Not only did the new particle have the correct spin, parity, charge, and strangeness, but its mass turned out to be 1674 MeV, almost exactly the predicted value! Thus the gaps in the decuplet were filled, and the theory of Gell-Mann and Ne'eman was confirmed in a remarkable way. The completed decuplet is shown in Figure 4.5 on page 79.

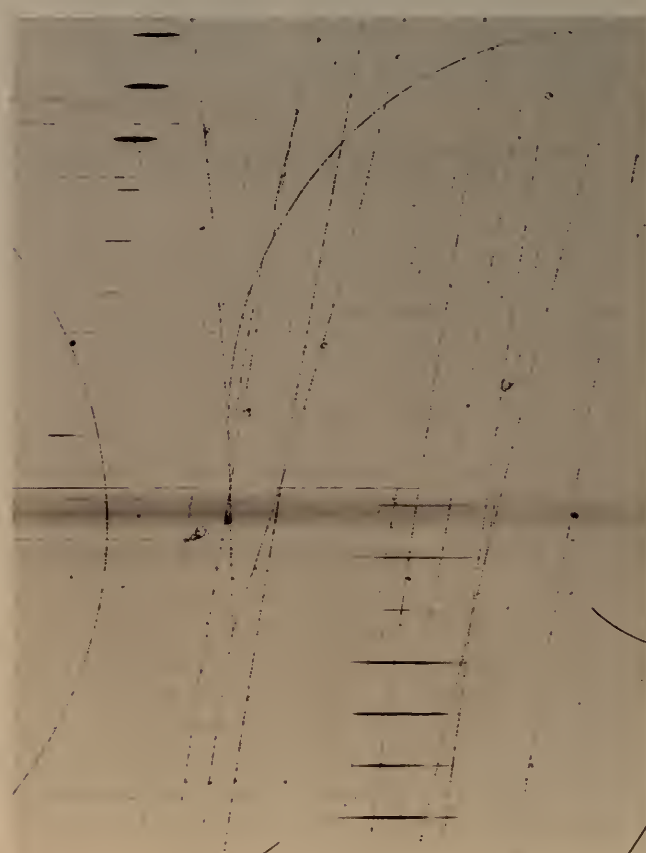
So far we have discussed only baryons, but it is natural that there be corresponding supermultiplets for the antibaryons. Not only that, but the mesons can be grouped in a similar way. Thus the Eightfold Way greatly simplifies our understanding of the long list of particles by grouping most of them into supermultiplets and then considering the members of each supermultiplet to be just slightly different manifestations of the same particle.

Fig. 4.4 This liquid hydrogen bubble chamber photograph is the third observation ever made of the production of an omega minus particle (Ω^-). The sketch beside the photograph shows the proper assignments of a particle to each track. The paths of neutral particles, which produce no bubbles in the liquid hydrogen and therefore leave no tracks, are shown by dashed lines. The presence and properties of the neutral particles are established by the analysis of the tracks of their charged decay products or the application of the laws of conservation of mass and energy, or a combination of both.

The incoming K^- meson from the Alternating Gradient Synchrotron collides with an unseen, stationary proton in the liquid hydrogen, producing a neutral K meson (K^0), a positive K meson (K^+), and the negative omega baryon (Ω^-). The Ω^- decays, after a lifetime of approximately one ten-billionth of a second, into a neutral lambda baryon and a negative K meson (K^-). The Λ^0 then decays into a proton (p) and a negative pi meson (π^-).

The photograph was taken in the 80-inch Liquid Hydrogen Bubble Chamber at Brookhaven National Laboratory.





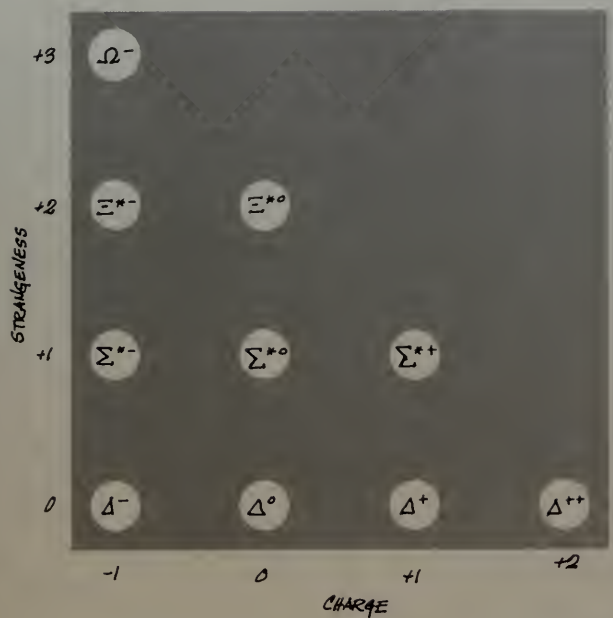


Fig. 4.5 States of the baryon with spin $\frac{3}{2}$, parity$^+$, in 1963.

4.7 Resonances Explained

To understand the next development in the theory of particles, we must briefly return to atomic physics and consider the states in which we might find a hydrogen atom. This atom consists of a nucleus with one orbital electron around it; according to quantum theory, this electron can only be in certain allowed orbits, while other orbits are forbidden. The orbits around an atomic nucleus correspond to definite values of the total energy, angular momentum, and parity of the atom, and since the orbits themselves cannot be observed, we generally talk about the atom in terms of the allowed energy states. A partial energy level diagram is sketched in Fig. 4.6 to illustrate this situation. The columns labeled *spin* and *parity* refer to the total angular momentum and parity of the entire atom.

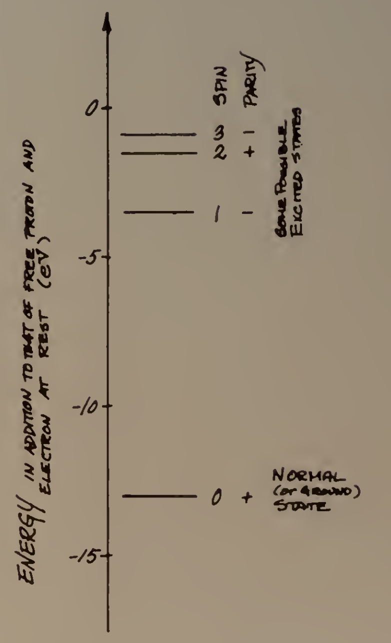


Fig. 4.6 Some allowed energy levels for a hydrogen atom.

Suppose now that we take a hydrogen atom in the normal (lowest energy) state and give it some extra internal energy. What happens to its internal structure? One possibility is that the atom will be changed to a state of higher energy and angular momentum, one of the excited states indicated on the diagram. This excited state will differ from the normal state in angular momentum, parity, and mass (because of the equivalence of the total energy of the atom with its mass, according to equation $E = mc^2$). Nevertheless, we still have a hydrogen atom. Changing its spin, parity, and mass have not changed its basic identity.

Of course, a real hydrogen atom does not stay in an excited state very long. It soon emits its excess energy (mass) in the form of a photon with energy $h\nu$ and returns to its normal state.

Let us now compare the behavior of particles with that of the atomic system just described. If we look at the complete list of particles, we find that many of the particles can be arranged in sequences similar to that of the excited states of hydrogen. Such a sequence is sketched in Fig. 4.7 for baryons with zero charge and strangeness −1. Once this arrangement is made, it is suggestive that the Λ^* particles with various masses may be excited states of the lambda particle. This hypothesis is reinforced by the behavior of the Λ^*, which does not live very long. It soon emits its excess energy (mass) in the form of a meson with appropriate energy and returns to its normal state as a Λ particle. The emission of a meson is appropriate here if the strong interaction is responsible for the formation of the Λ^*, since mesons are the carriers of the strong interaction. This is again analogous to the atomic case where the emitted particle is a photon, the carrier of the electromagnetic interaction that is responsible for the energy states of the atom.

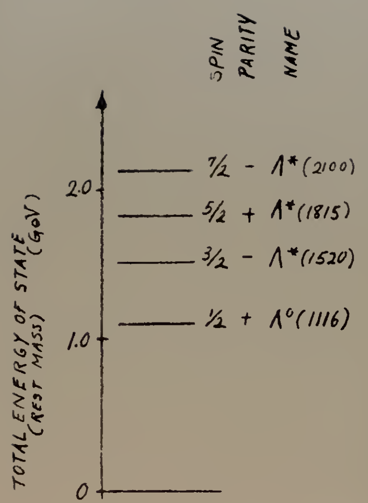


Fig. 4.7 Some allowed energy levels for a lambda particle.

A detailed study shows that all of the particles called resonances can be described simply as excited states of their more stable brothers. This allows a tremendous simplification in the way we look at the list of particles. There are just 35 basic particles, and all the others are just excited states of the basic 35.

4.8 Chaos Resolved?

At this point one might well ask if it is not possible to combine this understanding of resonances as excited states with the theory of the Eightfold Way to form a supertheory that encompasses all the strongly-interacting particles. Indeed it is, although it is not clear at this time whether such a combination will be adequate in every detail. The most promising approach seems to be the one that is called SU(6), a name that refers to the mathematical structure in which the theory is embedded. It is interesting that the mathematics of SU(6) was developed by the Norwegian Sophus Lie in the 19th century in a purely abstract study, with no idea that it would turn up in the physics of a century later.

Of course this classification is not intended to include the 9 particles that do not participate in strong interactions: electron, muon, and neutrinos, their antiparticles, and the photon. As we have noted in Chapter 3, the roles of all of these particles are quite well understood in their own right, with the exception of those in the muon family, whose existence is still a complete mystery.

The great advantage of the SU(6) scheme is that it takes all the hundreds of the known strongly interacting particles and describes them as small variations of three basic entities: the baryon, the antibaryon, and the meson. To give a crude analogy, many of the properties of people can be understood by considering each individual to be a relatively small variation of one of two basic types: male or female. Of course, in physics as in life, these small variations are extremely interesting.

Q1 In Fig. 4.1 and 4.2 are shown two unusual forked tracks which were identified as being produced by the decay of new kinds of particles. What alternative explanations could be given for the tracks, and how did the authors rule them out?

Q2 Using a quark model, as described in the epilogue, show how each meson and baryon in Table 1.1 could be constructed.

Q3 The Ξ^- particle is known to be unstable with a lifetime that indicates that strangeness is not conserved in its decay. What are the decay modes, with two particles in the final state, which are allowed by the seven absolute conservation laws?

Q4 A proton is the only baryon which is stable in the free state. List the reactions in one possible decay chain, starting with an Ω^- and ending with a proton and other products.

EPILOGUE The most fundamental question of particle physics is one that is still unresolved. Are elementary particles really elementary? Present evidence is that they are not, but no one is quite sure in what way they are not. The success of our efforts to find internal structure in the atom and then in the nucleus encourages the belief that internal structure may account for the many different observed states, or particles, whichever they are called. You will recall that the excited states of atoms were explained by changes in internal structure, changes in the orbits of their electrons. Since resonance particles seem to be excited states of the other particles, differing from them only in angular momentum and energy, we are led to wonder if particles also might have some internal structure.

There is a model, also proposed by Gell-Mann, which attempts to account for the observed properties of all strongly-interacting particles by assuming them to be constructed of more fundamental entities which he has called "quarks" (a word borrowed from a novel by James Joyce, because up to now they have been detected only by their "palpitant piping, chirrup, croak and quark"). A list of the properties of the three quarks and the three antiquarks follows.

Quarks and Antiquarks, Spin $\frac{1}{2}$

Symbol	*Baryon Number*	*Charge*	*Strangeness*
u	$\frac{1}{3}$	$+\frac{2}{3}$	0
d	$\frac{1}{3}$	$-\frac{1}{3}$	0
s	$\frac{1}{3}$	$-\frac{1}{3}$	-1
$\overline{u}$	$-\frac{1}{3}$	$-\frac{2}{3}$	0
$\overline{d}$	$-\frac{1}{3}$	$+\frac{1}{3}$	0
$\overline{s}$	$-\frac{1}{3}$	$+\frac{1}{3}$	$+1$

In this model each meson is made up of a quark-antiquark pair. This guarantees that the baryon number will have the correct value of zero, and any required value of charge or strangeness can be obtained by proper selection of the quarks. The rotational motion of the quarks about each other can be chosen to give the proper spin and mass to the composite particle. For example, a π^+ meson could be made of one u and one $\overline{d}$, symbolized as $(u\overline{d})$. That this combination has the correct properties as shown below.

	u	+	$\overline{d}$	=	π^+
charge	$(+\frac{2}{3})$	+	$(+\frac{1}{3})$	=	$+1$
baryon number	$(\frac{1}{3})$	+	$(-\frac{1}{3})$	=	0
strangeness	0	+	0	=	0

The baryons, according to this hypothesis, are constructed from three quarks, and the antibaryons from three antiquarks. To show how this goes, notice that a proton would have a structure (uud), which

gives a baryon number of +1, a charge of +1, and a strangeness of 0 as required. A Σ^+ particle on the other hand has the structure (uus) in order to get the proper value of strangeness (−1).

The quark scheme has the advantage not only of giving a tangible model for the structure of "elementary particles," but also of leading to correct mathematical predictions about the behavior of particles in collisions. In fact, there is only one great disadvantage: no one has ever observed a quark. This is particularly serious because a strong effort has been put forth to find them, ever since Gell-Mann's first suggestion in 1964. Furthermore, the assumption that they have fractional charges is in contradiction to the many experiments which show that the electronic charge is the smallest unit of charge in nature. A striking point about the current work in the field is the heuristic approach, so typical in the 20th-century science, that is being taken in this case. There are so many doubts whether the hypothetical quark exists. Perhaps it does not. But by assuming it, one can explain well some puzzling results. Victor Weisskopf of MIT, for example, asked whether he believed in the quark, is quoted as having told the story of Niels Bohr who visited a friend's house, noticed a horseshoe nailed over the door, and asked what it meant. His friend told him, "That brings luck." Bohr was astonished and said, "Do you really believe in this?" To which his friend replied, "Oh, I don't believe in it. But I am told it works even if you don't believe in it."

So we must finish on an ambiguous note, with an idea that is theoretically satisfying but experimentally dubious. Only further work can tell us what this means. But whatever the outcome, it is clear that work on their frontier is among the most interesting in all the sciences today.

The glass window for the 80-inch bubble chamber.

Laboratory Experiments in Particle Physics

L1 Introduction

In these pages, we describe five laboratory experiments which illustrate in quantitative detail the methods and physical principles of particle physics. Although they are collected here at the end of this unit, they can be performed immediately after Chapter 2, or in some cases even earlier. They are written so that any experiment can be selected and carried out independently of the others.

Before presenting the experiments, we review briefly some of the basic physical principles that will be applied. Since you will be applying certain formulas from these sections, it is important to have some idea where they come from and what they mean, although the ability to derive them is clearly less important.

The picture for Experiment 2 was taken in the Berkeley 10-inch bubble chamber, where the particle tracks we studied in Chapter 2 were also photographed. The pictures for all other experiments were taken in the Saclay 80-cm bubble chamber, located at the CERN Proton Synchrotron in Geneva, Switzerland. The CERN chamber was filled with liquid hydrogen, and the beam consisted of K^- mesons with energy low enough to stop in the chamber.

In the Saclay chamber, three views of each scene are taken simultaneously by different cameras to get good stereoscopic information. Only one of these views is reproduced here for each event. The magnetic field was 1.7 weber/square meter, out of the page in the pictures. This information allows us to analyze the behavior of the particles. Section L3, on page 88, shows the derivation of the relation between momentum and curvature:

$$p\ (\text{MeV/c}) = 3\ B(\text{web/m}^2)\ r\ (\text{cm})$$

Using this relation we find

$$p\ (\text{MeV/c}) = (3)\ (1.7) r\ (\text{cm}) = 5.1\ r\ (\text{cm})$$

The tracks left by negative particles curve counterclockwise. The pictures are reproduced with various different magnifications, which are indicated, so all measured distances must be scaled by appropriate factors to get true distances.

In doing these experiments you will frequently need to refer to various properties of the elementary particles. For this purpose we have reproduced here the Table of Particles from Chapter 1.

L2 Notes on Relativistic Mechanics

We discussed relativity in Unit 5, Chapter 20. There you learned that the mass of a particle depends on its velocity. For a particle with a mass m_0 when at rest (rest mass), the mass m when it is traveling at a velocity v is given by

$$m = \frac{m_0}{\sqrt{1 - v^2/c^2}}$$

where c is the velocity of light. Then, since the momentum p of a particle is given by its mass times its velocity, we find

$$p = \frac{m_0 v}{\sqrt{1 - v^2/c^2}}$$

Another result from relativity is the equivalence of mass and energy, according to the relation $E = mc^2$. Therefore the total energy of a particle is

$$E = \frac{m_0 c^2}{\sqrt{1 - v^2/c^2}}$$

The total energy can be thought of as having two parts: the rest energy m_0c^2, which is due to the rest mass of the particle, and the kinetic energy E_k, which is the added energy due to the fact that the particle is in motion (if it is). As usual, total energy equals rest energy plus kinetic energy:

$$E = m_0c^2 + E_k$$

It is sometimes convenient to have the total energy in terms of momentum instead of velocity because momentum is more easily measured in a bubble chamber. Such an expression is

$$E = \sqrt{(m_0c^2)^2 + (pc)^2}$$

In particle physics, energy is normally expressed in MeV. Also, instead of the mass, the rest energy m_0c^2 in MeV is usually given, and colloquially called "the mass." The momentum is given in the

TABLE L1 TABLE OF ELEMENTARY PARTICLES[a]

	Symbol[c]	Mass[b] (MeV)	Spin (Units of $h/2\pi$)	Parity	Baryon, Muon, or Electron Family Number	Charge (Units of $\|e\|$)	Strangeness	Lifetime (seconds)
Photon Family								
Photon	γ	0	1	–		0	0	Stable
Electron Family								
Electron	e^-	0.5	$\frac{1}{2}$		+1	–1	0	Stable
Positron	e^+	0.5	$\frac{1}{2}$		–1	+1	0	Stable
Electron's neutrino	ν_e	0	$\frac{1}{2}$		+1	0	0	Stable
Electron's antineutrino	$\bar{\nu}_e$	0	$\frac{1}{2}$		–1	0	0	Stable
Muon Family								
Mu minus	u^-	106	$\frac{1}{2}$		+1	–1	0	2.2×10^{-6}
Mu plus	u^+	106	$\frac{1}{2}$		–1	+1	0	2.2×10^{-6}
Muon's neutrino	ν_μ	0	$\frac{1}{2}$		+1	0	0	Stable
Muon's antineutrino	$\bar{\nu}_\mu$	0	$\frac{1}{2}$		–1	0	0	Stable
Meson Family								
Pi zero	π^0	135	0	–		0	0	0.8×10^{-16}
Pi plus	π^+	140	0	–		+1	0	2.6×10^{-8}
Pi minus	π^-	140	0	–		–1	0	2.6×10^{-8}
Kay plus	K^+	494	0	–		+1	+1	1.2×10^{-8}
Kay minus	K^-	494	0	–		–1	–1	1.2×10^{-8}
Kay zero	K^0	498	0	–		0	+1	0.9×10^{-10} [d]
Antikay zero	$\bar{K}^0$	498	0	–		0	–1	5.4×10^{-8} [d]
Eta	η^0	549	0	–		0	0	2×10^{-19}

	Symbol[c]	Mass[b] (MeV)	Spin (Units of $h/2\pi$)	Parity	Baryon, Muon, or Electron Family Number	Charge (Units of $\|e\|$)	Strangeness	Lifetime (seconds)
Baryon Family								
Proton	P^+	938	$\frac{1}{2}$	+	+1	+1	0	Stable
Antiproton	$\bar{P}^-$	938	$\frac{1}{2}$	+	–1	–1	0	Stable
Neutron	N^0	940	$\frac{1}{2}$	+	+1	0	0	10^3
Antineutron	$\bar{N}^0$	940	$\frac{1}{2}$	+	–1	0	–0	10^3
Lambda	λ^0	1116	$\frac{1}{2}$	+	+1	0	–1	2.5×10^{-10}
Antilambda	$\bar{\lambda}^0$	1116	$\frac{1}{2}$	+	–1	0	+1	2.5×10^{-10}
Sigma plus	Σ^+	1189	$\frac{1}{2}$	+	+1	+1	–1	0.8×10^{-10}
Antisigma, minus	$\bar{\Sigma}^-$	1189	$\frac{1}{2}$	+	–1	–1	+1	0.8×10^{-10}
Sigma zero	Σ^0	1192	$\frac{1}{2}$	+	+1	00	–1	$<10^{-14}$
Antisigma, zero	$\bar{\Sigma}^0$	1192	$\frac{1}{2}$	+	–1	0	+1	$<10^{-14}$
Sigma minus	Σ^-	1197	$\frac{1}{2}$	+	+1	–1	–1	1.5×10^{-10}
Antisigma, plus	$\bar{\Sigma}^+$	1197	$\frac{1}{2}$	+	–1	+1	+1	1.5×10^{-10}
Xi zero	Ξ^0	1315	$\frac{1}{2}$	+	+1	0	–2	3×10^{-10}
Antixi zero	$\bar{\Xi}^0$	1315	$\frac{1}{2}$	+	–1	0	+2	3×10^{-10}
Xi minus	Ξ^-	1321	$\frac{1}{2}$	+	+1	–1	–2	1.7×10^{-10}
Antixi, plus	$\bar{\Xi}^+$	1321	$\frac{1}{2}$	+	–1	+1	+2	1.7×10^{-10}
Omega minus	Ω^-	1673	$\frac{1}{2}$	+	+1	–1	–3	1.3×10^{-10}
Antiomega, plus[e]	$\bar{\Omega}^+$	1673	$\frac{1}{2}$	+	–1	+1	+3	1.3×10^{-10}

[a] Adapted from Particle Data Group, Physics Letters, August 1970. This list includes only particles with a lifetime of at least 10^{-19} sec.

[b] The "mass" quoted is actually the value of mc^2 in MeV, i.e. the rest energy.

[c] The bar over a symbol indicates an "antiparticle", which is the same as the corresponding "particle" except for having opposite family number, charge, and strangeness.

[d] A beam of K^0 or $\bar{K}^0$ mesons shows two different lifetimes: half the particles decay with the short lifetime and half with the longer one.

[e] Observed for the first time at U. of California, Berkeley, December 1970.

For example if $p = 100 \frac{\text{MeV}}{c}$,

multiply by c to get $pc = 100 \frac{\text{MeV}}{c} c$.

Then cancel the c's on the right,

giving $pc = 100$ MeV

which is numerically

equal to p in MeV/c.

units MeV/c, so that the quantity (pc) which appears in the last equation has the units MeV. Notice that pc in MeV is numerically equal to p in MeV/c.

For those who are interested, the proof of the relation between energy and momentum follows. The proof reduces both sides of that equation to an identity.

$$E = \sqrt{(m_0c^2)^2 + (pc)^2}$$

$$\begin{aligned}
E^2 &= (m_0c^2)^2 + (pc)^2 \\
&= m_0^2c^4 + \frac{m_0^2v^2c^2}{(1 - v^2/c^2)} \\
&= \frac{m_0^2c^4 - m_0^2v^2c^2 + m_0^2v^2c^2}{(1 - v^2/c^2)} \\
&= \frac{m_0^2c^4}{(1 - v^2/c^2)} \\
&= \left(\frac{m_0c^2}{\sqrt{1 - v^2/c^2}}\right)^2 \\
&= E^2 \qquad \text{Q.E.D.}
\end{aligned}$$

L3 Notes on Motion of a Charged Particle in a Magnetic Field

According to the right-hand rule, if the fingers of the right hand point along v and they can curl towards $\vec{B}$, the thumb points in the direction of $\vec{F}$. Thus in the diagram shown, the force on a positive charge will be out of the page.

In Sections 14.12 (Unit 4) and 22.2 (Unit 6), you have seen that a particle of charge q with a velocity $\vec{v}$, perpendicular to a magnetic field $\vec{B}$, experiences a magnetic force

$$F_{\text{mag}} = qvB$$

in a direction perpendicular to both $\vec{v}$ and $\vec{B}$, in accordance with the right-hand rule if q is positive, and in the opposite direction if q is negative. This force causes the particle to execute uniform circular motion in a plane perpendicular to $\vec{B}$. Such motion always requires the presence of a centripetal force

$$F_{\text{cent}} = \frac{mv^2}{r}$$

where r is the radius of the circle, and m is the relativistic mass of the particle.

Since the necessary centripetal force is supplied by the magnetic field, we can equate it with the magnetic force above, giving

$$qvB = \frac{mv^2}{r}$$

and by cancellation

$$qB = \frac{mv}{r}$$

so that

$$p = qBr$$

where we have made use of the definition of momentum, $p = mv$.

In our work we will measure p in MeV/c, B in weber/square meter, and r in centimeters. For singly charged particles, which have $q = 1.6 \times 10^{-19}$ coulomb, we find that

$$p\ (\text{MeV/c}) = 3B\ (\text{weber/m}^2)\ r\ (\text{cm})$$

If the velocity of the charged particle is not perpendicular to B then the above analysis holds for the component of momentum and the component of velocity that are in a plane perpendicular to B. The components of these quantities that are parallel to B are entirely unaffected by the field, so that instead of a circle, the path is a helix about a field line as an axis.

In mks units

$$pc\ (\text{joule}) = c\ (\text{m/sec})\ q\ (\text{coul})\ B\ (\text{web/m}^2)\ r\ (\text{m})$$
$$= (3 \times 10^{8})(1.6 \times 10^{-19})\ B\ (\text{web/m}^2)\ r\ (\text{cm}),$$
$$= 4.8 \times 10^{-13}\ B\ (\text{web/m}^2)\ r\ (\text{cm}).$$

but

$$1\ \text{eV} = 1.6 \times 10^{-19}\ \text{joule}$$
$$1\ \text{MeV} = 1.6 \times 10^{-13}\ \text{joule}$$

$$\therefore \quad pc\ (\text{MeV}) = \frac{pc\ (\text{joule})}{1.6 \times 10^{-13}} = \frac{4.8 \times 10^{-13}\ Br}{1.6 \times 10^{-13}}$$

$$pc\ (\text{MeV}) = 3\ B\ (\text{web/m}^2)\ r\ (\text{cm})$$

but P (MeV/c) is numerically equal to pc (MeV).

$$\therefore \quad P\ (\text{MeV/c}) = 3B\ (\text{web/m}^2)\ r\ (\text{cm}).$$

L4 Notes on the Use of the Curvature Template

A curvature template consists of a set of circular arcs of various radii drawn on transparent plastic. The arcs are labeled with their radii of curvature in cm. To measure an unknown curvature, one simply matches the template to the curve in question.

A suitable curvature template is available from The Ealing Corporation, 2225 Massachusetts Avenue, Cambridge, Mass., if you do not already have a supply in your class.

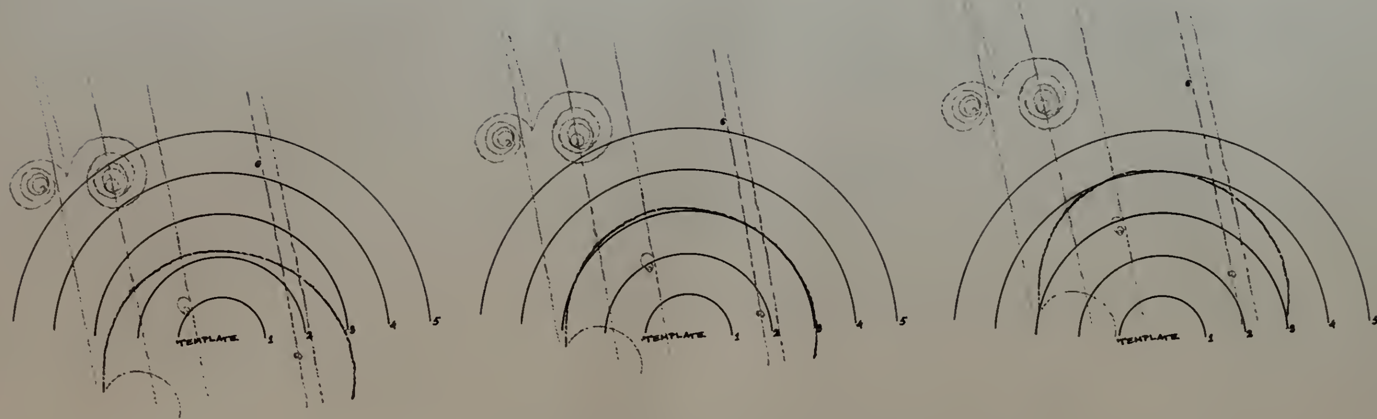
The radius of curvature of a particle track may vary along the track (an obvious example is the electron spiral). To measure a portion of the track, you look for an arc on the template which can be placed so that it passes right along the middle of the line of bubbles making the track, and stays in the middle for 10 cm or so.

The curvature template can be used most accurately on tracks that are reasonably long. The method of determining momentum from curvature works best for particles that are not too near the end of their range, so that their momentum is not changing too rapidly with distance.

A convenient way to test your template technique is to re-measure the radius of curvature at various points on the electron spiral of Fig. 2.1, and compare with your direct measurements.

L5 Experiment 1, Elastic Scattering and Conservation Laws

Background. In this experiment we will examine a collision of elementary particles in a bubble chamber to determine the identity of all particles involved and therefore whether or not the event is of



Use of the curvature template. Arc number 3 fits best.

the type known as elastic scattering. Elastic scattering is the simplest event that can take place when two elementary particles collide. It means scattering in which kinetic energy as well as total energy is conserved; in particle physics this will always be the case if the two particles present after the collision are of the same kinds as the two present before the collision, so that the event can be described in the form

$$A + B \longrightarrow A + B$$

Behind this use of terminology is an interesting bit of physics. As you learned in Unit 5, atoms can exist in various different energy states, and since $m = E/c^2$ these states have slightly different masses. However, whether it is in the ground state or in an excited state, a hydrogen atom is still a hydrogen atom. This is true despite the fact that some of its properties (notably mass and angular momentum) may be different in different states. A similar situation holds for nuclei: a nucleus is also not considered to change its identity when it goes into an excited state. In the case of elementary particles, however, rest mass and angular momentum are considered to be definite properties of a given kind of particle: if these are changed we have produced a "different" particle, not just an excited state of the same particle. This difference in terminology is traceable to the fact that we have an understanding of atoms and nuclei in terms of their constituent parts, while we do not as yet have any convincing evidence that elementary particles are composed of separate parts. Unless further developments along lines suggested in the Epilogue oblige us to change our ideas, we must continue to assume that elementary particles have no component parts. Thus, while an excited state of a nucleus or an atom can be explained in terms of a rearrangement of its parts, no such explanation is available to us in the case of elementary particles.

Elastic scattering can take place by means of any of the four basic forces, acting together or separately. However, the elastic scattering experiment presented here involves such small masses and short times of interaction that only the strong and electromagnetic interactions operate to a significant extent.

Notes on this Experiment. The laws needed to study this process are simply the relativistic forms of the law of conservation of momentum and the law of conservation of energy. You have studied nonrelativistic collisions in one dimension in Section 23.4, Unit 6. Now you will use the relativistic expressions and work in two dimensions. An elastic scattering event ordinarily involves three dimensions; however, we have chosen for this experiment a situation which can be reduced to two. The target particle is initially at rest when it is struck by the incident particle, so all particle tracks, before and after the collision, lie in the same plane. The result is a two-dimensional problem, in which momenta can be studied by means of a simple vector diagram. To simplify the analysis further, we have chosen an event which lies in the plane of the two-dimensional picture that you will use.

Recall that for the 80-cm Saclay bubble chamber, the momentum of a charged particle in the plane perpendicular to the magnetic field is proportional to the radius of curvature of the track in that plane, according to the relation $p = 5.1\ r$ where the momentum is in MeV/c and the radius of curvature is in cm. Notice however that the picture you will use is twice actual size, so all measured dimensions must be divided by two to get true dimensions. The curvature measurement is most easily made by using a curvature template, as described above, and dividing by *two* the radius obtained.

When we say twice actual size, etc., we will always be referring to linear dimensions, not to area.

To analyze the conservation of energy, you must also recall the relativistic expression for the total energy of a particle with rest mass m_0 and momentum p, which is

$$E = \sqrt{(m_0c^2)^2 + (pc)^2}$$

The total energy of a two-particle system is just the sum of the individual energies.

Procedure and Results.

1. Consider the photograph in Fig. L1 on the next page, which was taken using a K^- beam in the Saclay hydrogen bubble chamber. The beam enters from the bottom of the page, and negative tracks curve counterclockwise. All tracks lie in the plane of the picture. The event of interest is sketched in the margin on page 93.

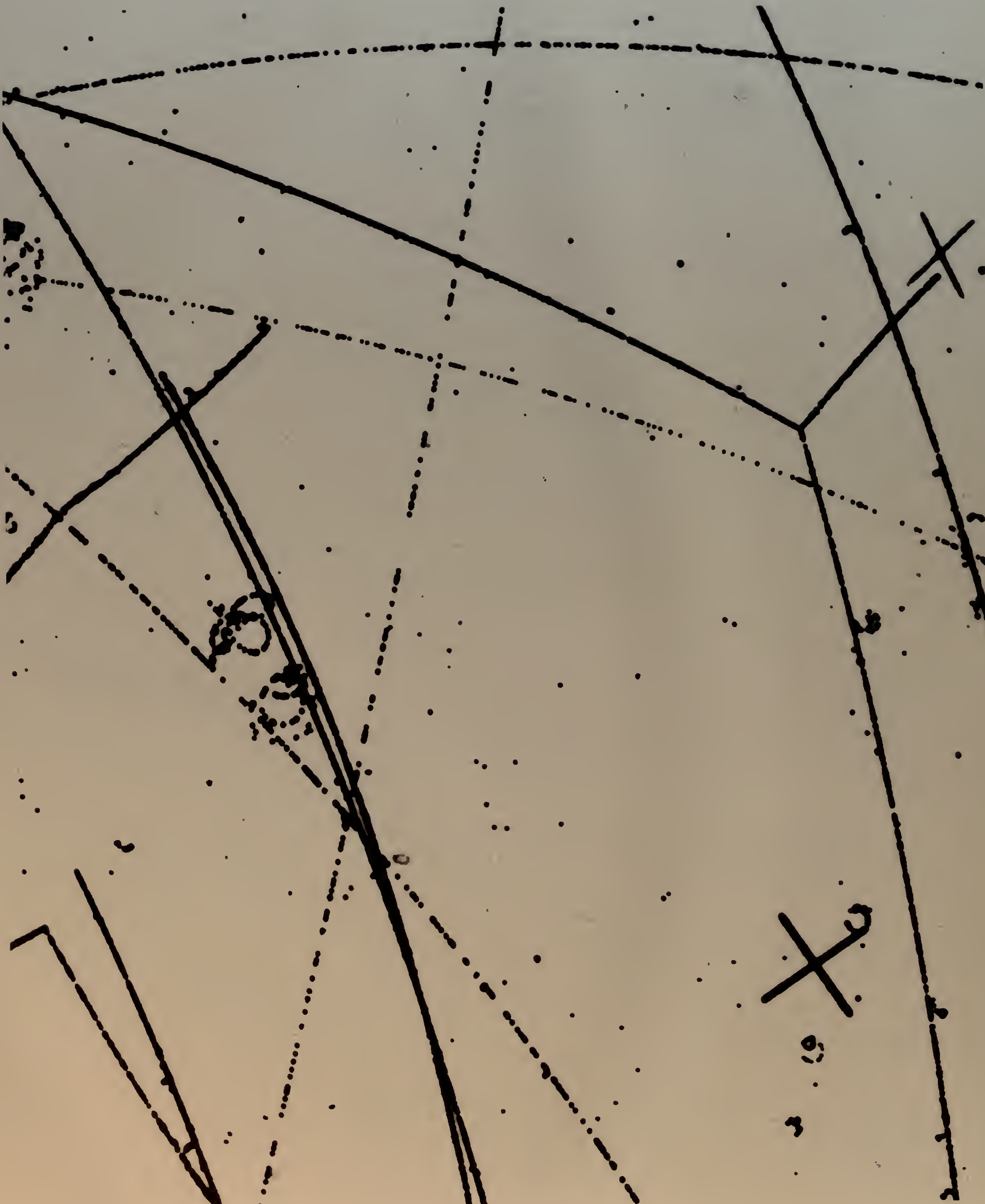
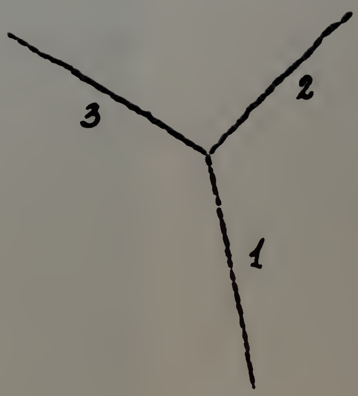


Fig. L1 Elastic scattering of K^- meson (twice actual size).

Make a sketch of this event. Assuming that the event does show elastic scattering, label each track with the symbol for the particle that you think made it and an arrow indicating the direction of motion.



2. What do you think the target particle is? Describe the event by an equation in the form A + B $\longrightarrow$ A + B, using the appropriate symbols for the actual particles.

3. Determine the momentum from curvature for tracks 1 and 3. You may also make this determination for track 2, but it will only be an estimate because that track is so short.

4. Using the law of conservation of momentum in the form $\vec{p}_1 = \vec{p}_2 + \vec{p}_3$, make a vector diagram and obtain $\vec{p}_2$ from $\vec{p}_1$ and $\vec{p}_3$. Note that the direction of a curved track is constantly changing, but remember that you are interested in the directions just before and just after the collision, i.e. lines tangent to the tracks at the collision vertex.

Does the direction of $\vec{p}_2$ obtained in this way agree with the observed direction?

5. Does the magnitude of $\vec{p}_2$ obtained in step 4 seem reasonable in the light of your estimate in step 3?

6. From the length of track 2, which is the full range of that particle since it does come to rest, find the initial momentum from the range versus momentum graph for protons in Fig. L3, page 96. If this agrees with the value from your vector diagram, it is a strong confirmation that the particle which made track 2 is a proton.

7. Notice that you have not yet used the law of conservation of energy. You may use this law now to determine conclusively the rest mass and thus the identity of the particle which made track 3. Is particle 3 the same as the incident particle or not?

The identity of particle 1 is known from the incident beam that was chosen. The identity of the target, which is called particle 2 after it is scattered, is known from the choice of the chamber liquid and confirmed by the range test made in step 6. All the momenta are known from the vector diagram of step 4. Thus, you can write the law of conservation of energy and solve for the mass of particle 3. The mass and its charge (how do you know the charge?) will allow you to identify particle 3 without any doubt. Is this event really a case of elastic scattering?

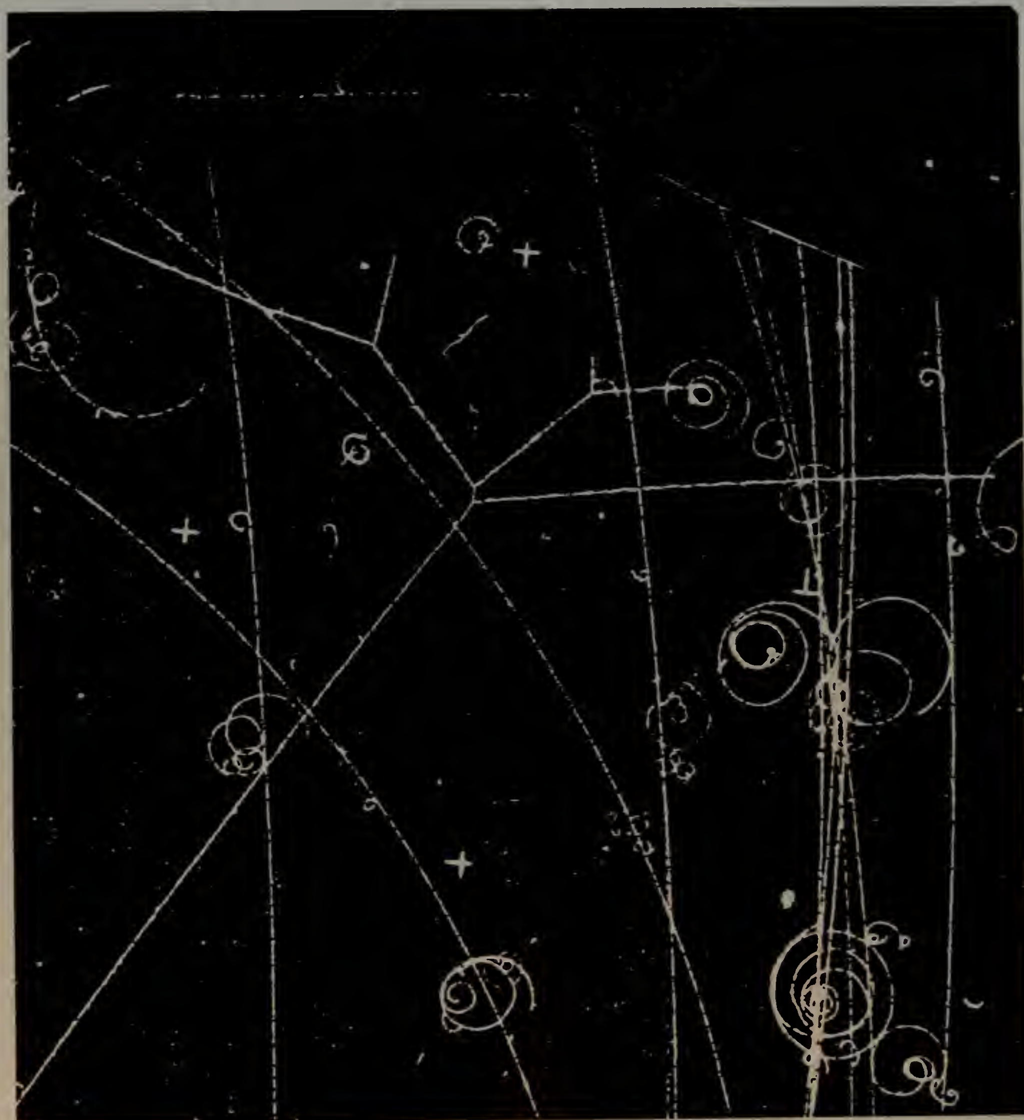


Fig. L 2 Multiple proton collisions (actual size).

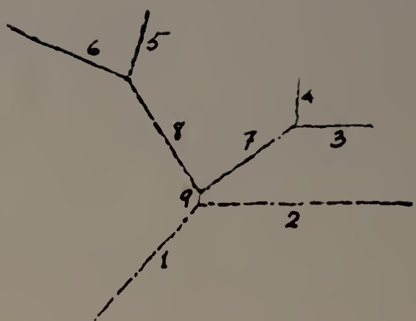
L6 Experiment 2, Conservation of Energy

Background. As you know, one of the most fundamental laws of physics is that of conservation of energy. In this experiment, you will be able to follow a complicated series of events to see in a rather graphic way how the initial energy of a single particle is distributed among many particles by successive collisions.

Since this is a bubble chamber experiment, as the charged particles go through the hydrogen in the chamber they lose energy to it, energy that goes ultimately into the formation of the bubbles that we observe. As in most other situations where energy is dissipated, the kinetic energy is finally transformed into heat energy. Thus, the overall flow of energy in this experiment may be described as

$$\begin{pmatrix}\text{kinetic energy of}\\ \text{incident particle}\end{pmatrix} \longrightarrow \begin{pmatrix}\text{kinetic energy of}\\ \text{struck particles}\end{pmatrix} \longrightarrow \begin{pmatrix}\text{heat of formation}\\ \text{of hydrogen bubbles}\end{pmatrix}$$

Notes on this Experiment. This experiment will use the same multiple proton scattering event that was used in Section 2.3. The picture is reproduced here for convenience, as Fig. L2, and a sketch with the track numbers is included in the margin. As you recall, this picture was taken with the Berkeley 10-inch bubble chamber; the incident particle was a proton, coming in at the lower left and striking another proton in the hydrogen, thus initiating a series of proton-proton elastic collisions.



The analysis of this event will make use of the range versus momentum graphs (Fig. L3 on the next page), which are well-established, both theoretically and experimentally. As they imply, if the initial momentum of a given type of particle is known, then the distance it will travel before coming to rest (the range) in liquid hydrogen is also known. Conversely, if we measure the range of a particle on a bubble chamber picture, we can go to these graphs to find out what the initial momentum of that particle was.

To apply this technique to the event in question, we start at the ends and work backward. The three-dimensional stereo pictures of the same event show that none of the tracks deviates sharply from the plane of the two-dimensional photograph, with the possible exception of track 9, which is relatively short anyway. Therefore, we will measure track lengths on the two-dimensional picture for simplicity, realizing that it would be necessary to go to three-dimensional measurements to achieve high accuracy.

Procedure and Results.

1. Measure the lengths of tracks 2, 3, 4, 5, and 6. Since all these protons stop, track length = range, and you can find the initial momentum for each track from Fig. L3. For example, track 6 is about 4.1 cm long in real space, so the initial momentum of particle 6 must have been about 210 MeV/c.

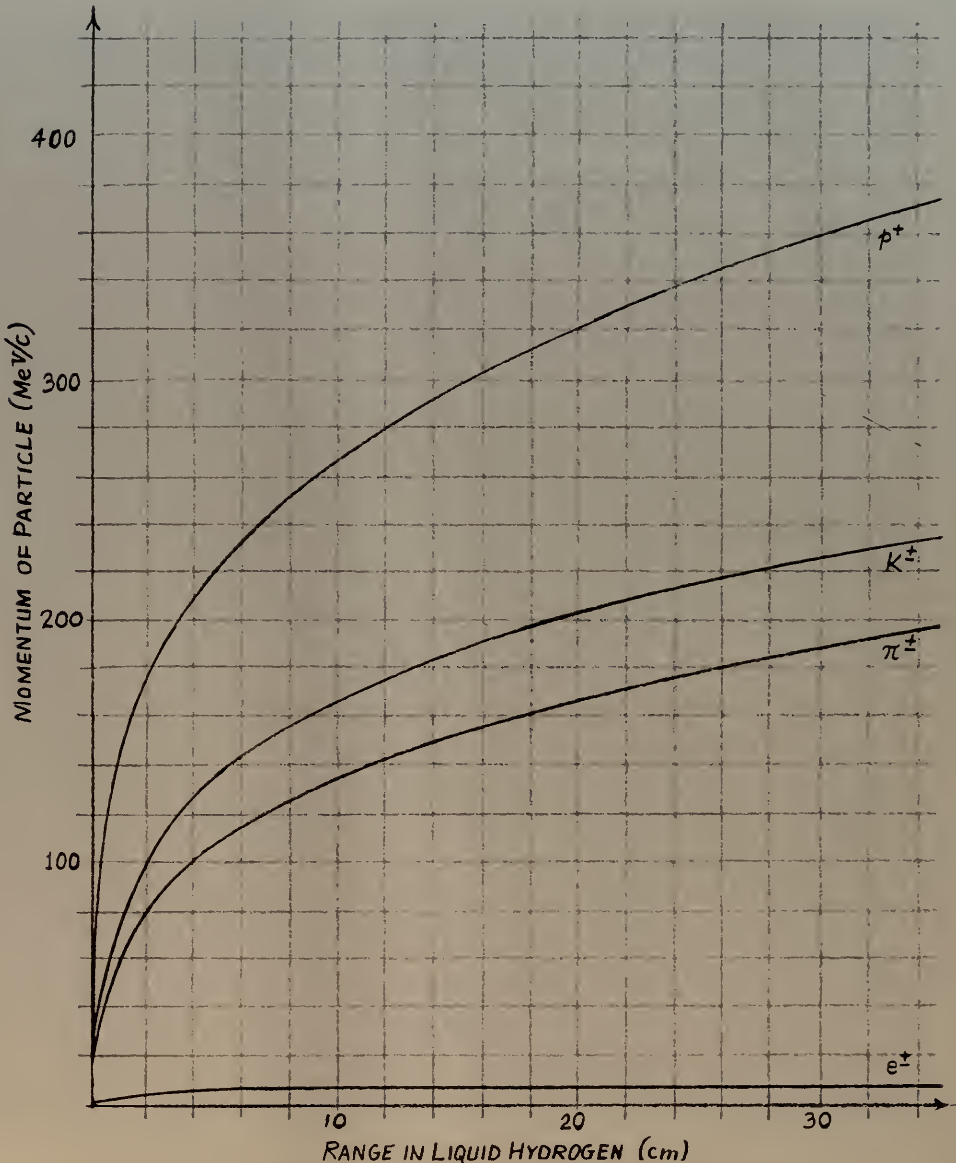


Fig. L 3 Range versus momentum curves for various particles. The curve for electrons is less precise than the others.

2. Convert these momenta to kinetic energy. A nonrelativistic calculation can be used because the protons do not travel very fast. Thus

$$E_k = \tfrac{1}{2}\, mv^2 = \frac{(mv)^2}{2m} = \frac{p^2}{2m} = \frac{(pc)^2}{2\,(mc^2)}$$

where mc^2 for protons is about 1000 MeV, while pc in MeV is numerically equal to the momentum p in MeV/c from the graph. For example, the kinetic energy of particle 6 is about 22 MeV.

3. Next, add the outgoing kinetic energies at each vertex. Since kinetic energy is conserved in elastic collisions, this will give the kinetic energy of the incoming particle. If the kinetic energies of particles 5 and 6 are 13 MeV and 22 MeV, then the kinetic energy of particle 8 must be 35 MeV.

4. Now you must convert again to get the momenta of particles 7 and 8 at the ends of their tracks. The relevant equation is a variation of that used in step 2:

$$p\ (\text{MeV}/c) = pc\ (\text{MeV}) = \sqrt{2\,(mc^2)\,E_k}$$

For example, the final momentum of particle 8 is about 265 MeV/c.

5. These momenta and the graph of Fig. L3 allow you to calculate the "residual range," the additional distance a particle would have gone if it had not suffered a collision. When the residual range at the end of a track is added to the length of that track, the sum is equal to the full range, and that in turn allows you to find the momentum of the particle at the beginning of its track. For particle 8 the residual range corresponding to its final momentum of 265 MeV/c is 10 cm and its measured track length is 2.3 cm, so that its full range would be 12.3 cm, which implies an initial momentum of 285 MeV/c.

6. By repeating this process for particle 7 and then for particle 9, you can find the total kinetic energy brought in by particle 1.

7. Your result should be of the order of 100 MeV. The energy of this incoming proton can also be found directly by measuring the curvature of its track, getting the momentum, and converting to kinetic energy as above. The curvature template will assist you in measuring the track.

8. You should get about the same value of energy both ways, which indicates that the kinetic energy of the incident proton is nicely accounted for in the energy loss of the various secondary protons as they slow down in the chamber.

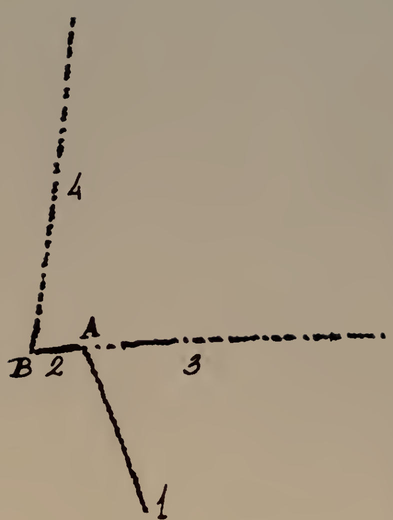
L7 Experiment 3, Inelastic Scattering and High-Energy Reactions

Background. In this experiment we will look at one of the most interesting things that can happen when two elementary particles come together: they react and produce two entirely different products! Your task will be to examine the particle tracks and describe the event which has taken place, identifying the particles involved.

Notes on this Experiment. When we bring together two particles that can interact via the strong interaction they do interact

in this way and they do so very rapidly, in times of the order of 10^{-23} sec. Even at speeds near the velocity of light, a particle can barely traverse a proton diameter during such a short time. Given the identity and energy of both the incident particle and the target particle, there are often several possible results of such a collision, but they all must satisfy the appropriate conservation laws. These include the absolute conservation laws for momentum, energy, charge, and baryon number. In the case of strong interactions they also include conservation of strangeness.

In this experiment a beam of K^- mesons is incident on the Saclay 80-cm hydrogen bubble chamber, with a momentum chosen so that the particles will come to rest near the middle of the chamber unless something happens first, such as the elastic scatter of Experiment 1. The problem is to figure out which of the many possible reactions actually took place.



Procedure and Results.

1. Figure L4 and the sketch in the margin show an event in which a K^- meson and a proton interact, with both particles at rest. We have used light lines to show tracks with light bubble density. Using the Table of Elementary Particles, see if you can determine the five possible reactions which result in a two-particle (baryons and/or mesons) final state (i.e. particles 2 and 3), and which satisfy the laws of conservation of energy, charge, baryon number, and strangeness.

2. The K^- beam enters from the bottom of the page and ends at vertex A. What kind of particle do you think must be the target particle at A?

3. Why do the two tracks that originate at vertex A indicate that the K^- was at rest at the time of the interaction? (See Section 2.7 if you are not sure.)

4. Of the five possibilities you have found in step 1, two can be ruled out here because they have only neutral products, which would not leave bubble tracks.

5. Since the magnitudes of the momenta of the particles that made tracks 2 and 3 are equal, the marked difference in bubble density between them must be due to a difference in mass. Recalling that for a given momentum the heavier (slower) particle produces a heavier bubble density, which of these two is the heavier? Is its electric charge positive or negative? Questions like these should allow you to narrow the field still further. What particle do you think made track 2? Call this "particle 2."

Fig. L4 Inelastic event produced by K^- meson and proton (twice actual size).

6. Assuming that track 3 is left by a π^+ meson, and using the conservation laws and the identities of the other two particles in the reaction at A, determine the baryon number, charge, and strangeness of particle 2. (This question does not require any measurements on the photograph.)

7. Determine the mass of particle 2 by measuring the momentum of the π^+ meson and applying conservation of energy and momentum to the interaction at A in a way similar to the method of Experiment 1, but remembering that both the K^- and the p^+ are essentially at rest here before the reaction (see Section 2.7 of this unit).

8. Identify particle 2 by using the Table of Particles and the measured mass as well as the quantum numbers determined in question 6. Is it the particle you expected from your analysis in step 5?

9. Notice in the photograph that particle 2 travels to vertex B, where a sharp kink appears in the track. What do you think happened at B? This will be the subject of Experiment 5.

L8 Experiment 4, Detective Work

Background. The first step in the analysis of a set of bubble chamber pictures is called scanning: looking at the pictures one by one to see if they contain events that are of interest in the particular experiment being performed. As you learned in the guided tour of Chapter 2, it is possible to tell a great deal about bubble chamber events just by looking at them and applying your knowledge of the physics involved. This is especially true of events produced by a beam with energy low enough to stop in the chamber, since then the number of different kinds of events that can occur is not very large.

The general procedure at the beginning of an experiment is to calculate the available energy and use the Table of Elementary Particles, in conjunction with the conservation laws, to determine all possible reactions, much as you did in question 1 of Experiment 3. Events found in the pictures can then be compared with the expected possibilities to see which they may be.

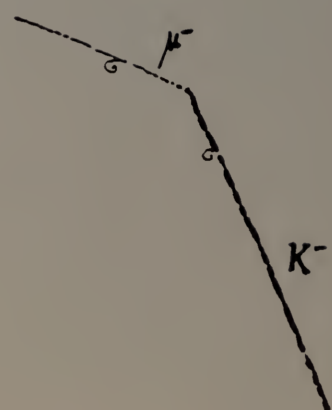
Notes on this Experiment. In this experiment you will look at a complete picture from the Saclay 80-cm hydrogen bubble chamber. The incident beam consists of K^- mesons which have a rather low momentum so that most of them stop in the chamber. The picture is reproduced at approximately actual size in Fig. L5 on page 102, and the six beam tracks have been numbered at the bottom for

convenience. There are several extra tracks that are rather dotted and pass straight through the chamber, but we will ignore them.

By showing you examples of the most common types of events in this experimental situation, we hope to prepare you to recognize them when you see them again. We will first lead you through a "complete scan," identifying every event in this picture and discussing that identification. Then you will be on your own to do a complete scan of an unknown photograph showing similar kinds of events.

Procedure and Results, Part I. Taken in order, the events in Fig. L5 are sketched and then analyzed according to the appropriate conservation laws.

Beam Track 1. Decay of a K^- Meson into a Muon and Neutrino:



	$K^- \longrightarrow$	$\mu^- +$	$\bar{\nu}_\mu$
charge	-1	-1	0
	-1	-1	
baryon number	0	0	0
total baryon number	0	0	

The decay is a weak interaction process, so strangeness need not be conserved. The $\bar{\nu}_\mu$ is neutral so it leaves no track. Actually one cannot distinguish between the tracks of a muon and a pi meson by just looking, so this event could also be $K^- \longrightarrow \pi^- + \pi^0$. For standardization we will always write down the muon possibility, but put a question mark after the equation to emphasize that there are other equations that could correspond to these tracks.

Beam Track 2, Decay of a K^- Meson into a Muon and Neutrino:

Although at first sight it looks different, this is the same kind of event as that produced by beam track 1. Notice how the track suddenly becomes dotted, indicating an increase in velocity: the μ^- goes faster than the K^- with similar momentum.

Beam Track 3, Lambda Production and Decay:

Since the negative K^- track simply ends, with no charged tracks continuing, its charge must have been canceled by the positive charge on a proton. Thus the initial reaction is

$$K^- + p^+ \longrightarrow \text{neutral particles}$$

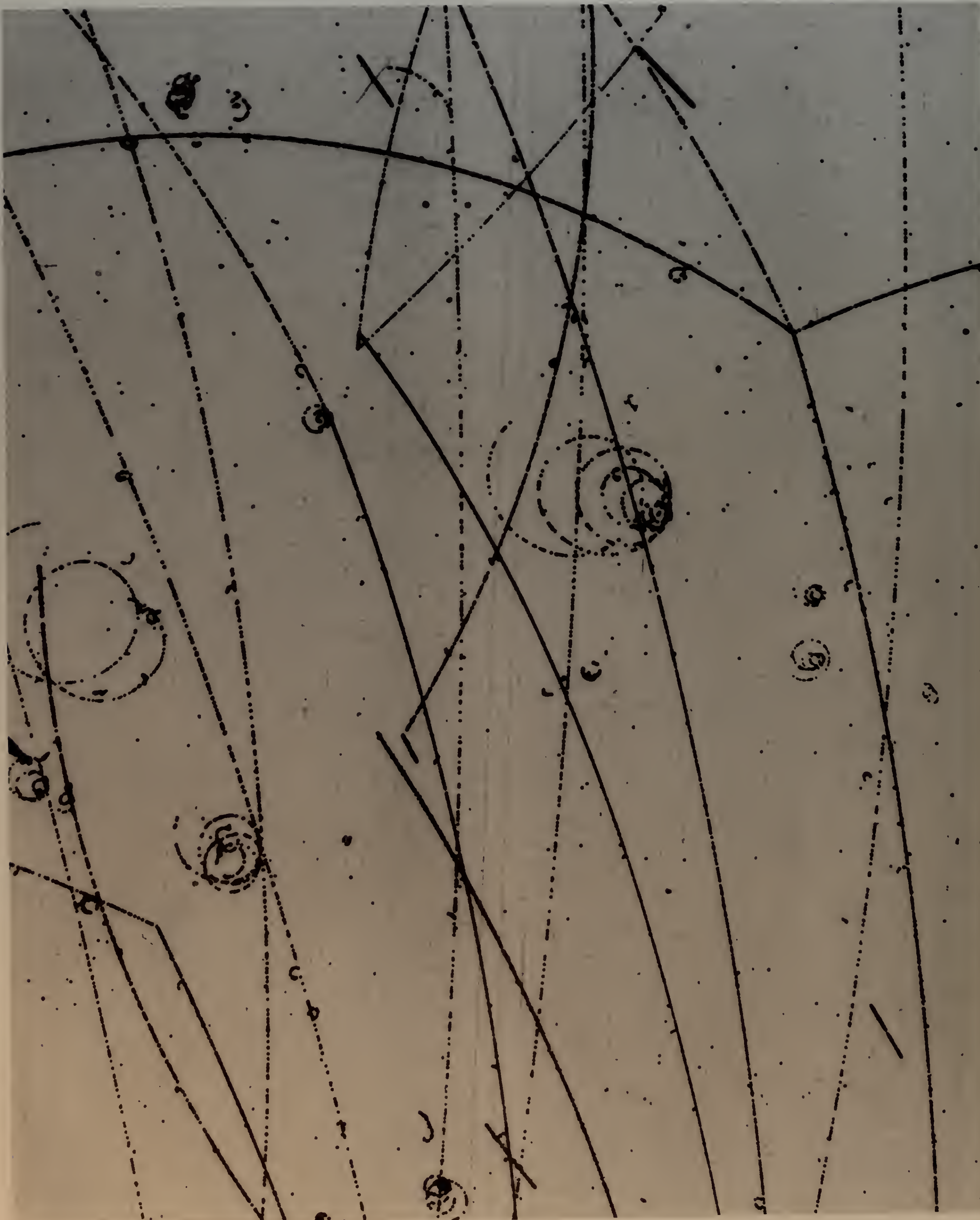


Fig. L5 A typical scene in a bubble chamber (approximately actual size).


1
2
3
4
5
6

One baryon enters this reaction, so conservation of baryon number requires that there must be a baryon among the products. The K^- and the proton are strongly interacting particles, therefore they react via the strong interaction. Since the strong interaction conserves strangeness, and the total strangeness of the entering particles is -1, we expect one of the products to have strangeness -1 also.

The nearby V seems to point back towards the end of the K^-: it could be due to the decay of one of the neutral products of the first reaction. The short, heavy track in the V is characteristic of a low-energy proton, and the whole V is characteristic of the decay of a lambda particle into a proton and a pi minus meson:

$$\Lambda^0 \longrightarrow p^+ + \pi^-$$

You can check conservation of charge and baryon number in this decay. Strangeness is not conserved in the decay because it goes via the weak interaction.

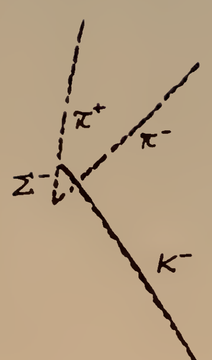
Identification of the lambda from its decay allows us to complete the analysis of the production reaction. The equation is

$$K^- + p^+ \longrightarrow \Lambda^0 + \pi^0 \qquad (?)$$

as you can see by checking the conservation laws appropriate to strong interactions. However, notice that this event might have actually gone through an additional step as follows:

$$\begin{array}{l} K^- + p^+ \longrightarrow \Sigma^0 + \pi^0 \\ \qquad\qquad\qquad \llcorner\!\!\longrightarrow \Lambda^0 + \gamma \end{array}$$

Decay of the Σ^0 is via the electromagnetic interaction, so it is rather rapid. The photon is neutral and unobservable, so the general appearance of this event would be the same as that of the first possibility. In cases like this we will again standardize, always writing down the direct production of a Λ^0, but putting a question mark to remind us that there is another possibility. Actually, the second possibility is the more likely one, but the first one is a sort of minimum that we can be sure of since there is no visual evidence for the Σ^0. As usual we can only distinguish between these possibilities by actual measurement.



Beam Track 4, Sigma Minus Production and Decay:

This is a slight variation of the type of event studied in Section 2.6 and is the same type as the event studied in Experiment 3. The appropriate equations are

$$\begin{array}{l} K^- + p^+ \longrightarrow \Sigma^- + \pi^+ \\ \qquad\qquad\qquad \llcorner\!\!\longrightarrow \pi^- + n^0 \end{array}$$

Do the signs of the electric charges assumed agree with the directions of curvature of the tracks? Are the appropriate conservation laws satisfied at each step?

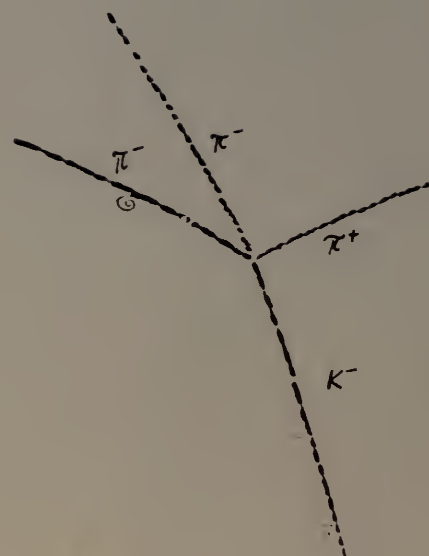
Beam Track 5, No Reaction:

Here the K^- particle goes straight on through. Apparently it had a higher momentum than the K^- particles in tracks 3 and 4, since they stopped in the chamber. This particle also did not happen to decay like the particles in tracks 1 and 2.

Beam Track 6, Decay of K^- Meson into Three Pi Mesons:

This is another way in which the K^- meson can decay. Actually 18 different decay modes have been observed for this particle! Check the charge assignments against the curvatures of the tracks and test the equation for the decay against the appropriate conservation laws. The equation is

$$K^- \longrightarrow \pi^- + \pi^- + \pi^+$$



Actually, as mentioned under beam track 1, some of the "pi meson" tracks may actually be muons. Only precise measurement can tell, but the equation written here is by far the most likely possibility.

Procedure and Results, Part II. Now it is your turn. Can you tell what happened to the seven numbered K^- beam tracks in Fig. L6 on the next page? The experimental situation is the same as in Part I. The Table of Particles and the conservation laws should allow you to make a reasonable hypothesis in each case.

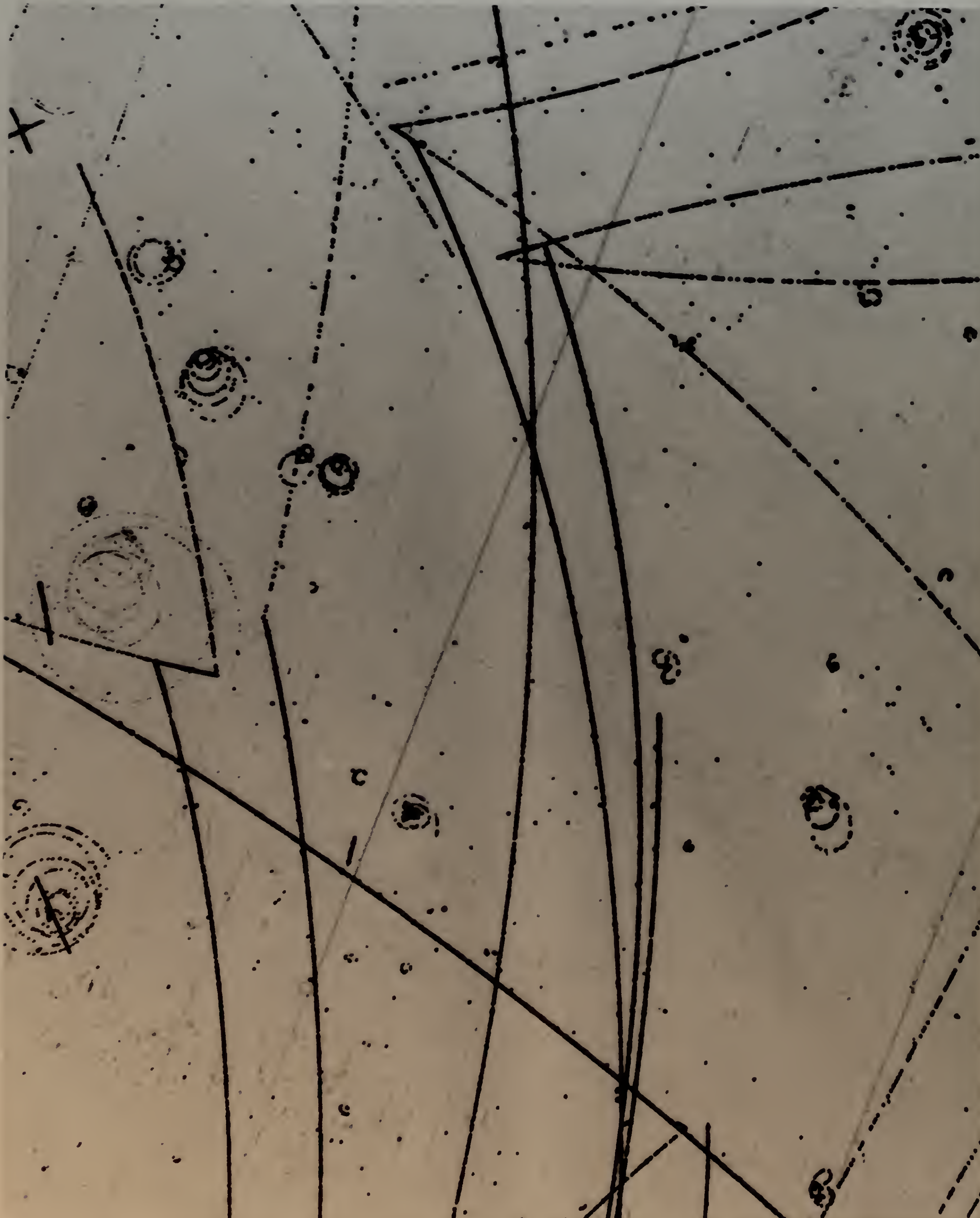


Fig. L 6   Another scene in a bubble chamber (approximately actual size).

L9 Experiment 5, Decay of Particles and Mean Lifetime

Background. In this experiment we will investigate the decay of an elementary particle, a process which is essentially the same as the decay of a radioactive nucleus. You will recall from Unit 6, Section 21.5 that radioactive decay is a statistical process. That is, although it is impossible to predict whether a given particle will decay in a given time interval, it is still possible to predict what fraction of a large sample of identical particles will decay in such a time interval. Furthermore, it is found that the fraction of the particles present at any time which decay per unit time is a constant λ (the decay constant), independent of the time t at which λ is measured. If N is the number of undecayed particles present at time t and ΔN is the number that decay in a short time interval Δt, starting at t, then the decay constant is calculated as $\lambda = \Delta N/N\Delta t$.

A useful way of restating the decay law is that the *probability* that a particle of a given type will decay in unit time equals λ, a constant characteristic of that type of particle. This gives the radioactive decay law the mathematical form shown in question 7 below. The value of λ can be determined by experiment.

Since the decay law is a statistical law, if we start with a sample of unstable particles and observe the actual values of λ at various times we will find that these observed values fluctuate about a certain mean value, with the relative size of the fluctuations increasing as the actual number of decays observed in the interval gets smaller.

Fluctuations in the decay process are entirely analogous to those familiar in coin tossing experiments, where the fraction of heads obtained in a run of several tosses is not always precisely 0.5, but fluctuates about that number, while the size of the fluctuations actually observed decreases as the number of tosses is increased. To be specific, if f_H is the fraction of the tosses which come out heads, out of 2 tosses one might easily find the value of f_H at 0 or 1.0, while in a run with 2 million tosses f_H will be exceedingly (over 99%) likely to lie between 0.499 and 0.501.

In particle physics it is customary to quote the *lifetime* in seconds (Greek tau) $\tau = 1/\lambda$ for a particle instead of the decay constant itself.

Notes on this Experiment. The pictures to be used contain tracks of Σ^- (sigma minus) particles produced in the reaction kay minus and proton go to sigma minus and pi plus:

$$K^- + p^+ \longrightarrow \Sigma^- + \pi^+$$

where the K^- comes to rest before interacting with the proton. The K^- beam is a secondary beam from the Proton Synchrotron at

CERN, and the protons are the nuclei of hydrogen atoms in the Saclay 80-cm bubble chamber.

Conservation of momentum requires that when both the K⁻ and the proton are initially at rest, the vector sum of the momenta of the reaction products must be zero. Thus the Σ^- and the π^+ must leave the production vertex in exactly opposite directions, a fact that you have already observed in Fig. L4. Since the Σ^- is much heavier than the π^+, and the magnitudes of their momenta are equal, the velocity of the Σ^- is much lower than that of the π^+. This accounts for the solid track left by the Σ^- and the much lower bubble density along the track of the pi meson.

The Σ^- particles themselves lose energy rapidly as they travel through the chamber, and they would be expected to come to rest with a range of about a centimeter. However, they are also very unstable, so that most of them actually decay while still in flight by the process sigma minus goes to pi minus and neutron:

$$\Sigma^- \longrightarrow \pi^- + n^0$$

where the neutron, being electrically neutral, leaves no track, while the π^- track starts from the decay vertex. Figure L7 (opposite) shows one example of this possibility, and nine more are collected in Fig. L8 on page 112.

In the few cases where the Σ^- particle actually does come to rest, it reacts with a proton in the hydrogen to produce a neutron and other neutral products, so that no visible tracks leave the end of the Σ^- track, as seen in Fig. L7.

The process by which a charged particle slows down in liquid hydrogen has been well studied, leading to tables of range versus initial momentum for any particle. Fig. L3 was drawn from such tables. Since all the Σ^- are produced by K^-, p^+ reactions at rest, they all have the same initial momentum of 173 MeV/*c* as derived in the optional problem below, and we can construct a table of time of flight versus track length for these Σ^- particles. This information is presented in a table on page 110. Distinguish between *range*, the distance a particle would go before coming to rest, and *length*, the length of a track, which may be terminated by decay before the particle comes to rest.

(a) Production and decay

(b) Production and reaction with proton.

Fig. L 7 Events containing a sigma minus (Σ^-) particle (twice actual size).

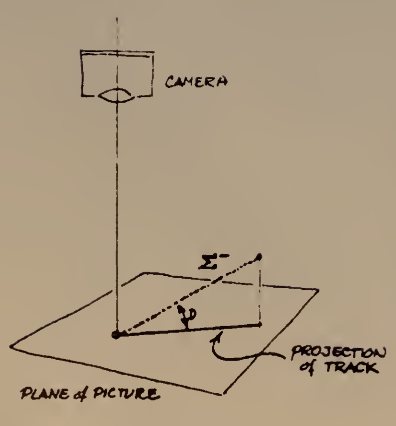
TABLE L2

TABLE FOR CONVERSION OF LENGTH TO TIME OF FLIGHT FOR Σ^- PARTICLES WITH INITIAL MOMENTUM 173 MeV/c IN LIQUID HYDROGEN

Projected Length in Picture (mm)	*True Length in Chamber* (average; mm)	*Time of Flight* (sec)
0.5	0.3	0.08×10^{-10}
1.5	1.0	0.23×10^{-10}
2.5	1.6	0.38×10^{-10}
3.5	2.2	0.53×10^{-10}
4.5	2.9	0.69×10^{-10}
5.5	3.5	0.85×10^{-10}
6.5	4.2	1.02×10^{-10}
7.5	4.8	1.19×10^{-10}
8.5	5.4	1.36×10^{-10}
9.5	6.1	1.54×10^{-10}
10.5	6.7	1.73×10^{-10}
11.5	7.4	1.94×10^{-10}
12.5	8.0	2.16×10^{-10}
13.5	8.6	2.37×10^{-10}
14.5	9.3	2.65×10^{-10}
15.5	9.9	2.95×10^{-10}

In this table the relation between true length and the time of flight is exact. The relation between projected length and true length holds only on the average, and is calculated assuming pictures with 2× magnification.

Basically, the lifetime measurement consists of taking a random sample of Σ^- tracks, measuring their lengths, converting to individual decay times, and then recording the number remaining versus time since production.



In order to do this you will make measurements on a 2-dimensional picture of the Σ^- event, and since the tracks may actually be dipping at some angle D with respect to the plane of the picture, the projected length that you measure will in general be less than the true length of the track. It is necessary to correct for this, and to do so we assume that the directions of the Σ^- tracks are completely random. This assumption is reasonable, since production occurs from a K^-p^+ blob formed essentially at rest, with no particular direction of motion.

This assumption may be illustrated by drawing a small sphere about the production point. Then the track is equally likely to pass through any point on the sphere, and a random sample of tracks will pass through random points distributed all over the sphere. Therefore, the probability for a track to pass through a specified area of the sphere is equal to that area divided by the area of the entire sphere. On this basis it can be shown that the average ratio of track length to projected length is 1.28, so all measured projected

lengths will be scaled up by this factor. This of course does not give the true length of each track, but since it is correct on the average, it will give exactly the same results as using the true lengths measured in three dimensions, so long as there is a large enough sample of tracks.

The actual calculation is omitted here because it involves trigonometry and calculus. The derivation is given in the Teacher Guide.

We must also divide the measured lengths by 2 to take into account the 2× magnification of the pictures. Therefore, to get average true length in real space from projected length measured in the picture we multiply by 0.64 (that is, 1.28 ÷ 2).

For Σ^- particles that react with a proton rather than decaying, we simply use the full range of 10.5 mm obtained from the range versus momentum tables for the initial momentum of 173 MeV/c.

Optional Problem. If you wish to calculate the initial momentum of the Σ^-, it can be done by using the relativistic law of conservation of energy. Let p be the magnitude of the momentum of the Σ^- or the π^+. Why are they equal? Then recall that the relativistic total energy of a particle is

$$E = \sqrt{(m_0c^2)^2 + (pc)^2}$$

where E, m_0c^2, and pc are usually in MeV and p is then in MeV/c. The necessary masses are available in the Table of Particles.

Procedure and Results.

1. The 11 events in Figs. L7 and L8 have been selected at random from a large sample of Σ^- (sigma minus) production events of the type discussed above. Only a small section of each picture is reproduced, since only the identification and the length of the Σ^- track are necessary for this experiment. The incoming K^- meson comes from the bottom of the picture in every case.

Measure to the nearest millimeter the projected length of the Σ^- tracks in the pictures for all decays. Also record and count all Σ^- that undergo a reaction with a proton instead of decaying. You can then think of a series of length intervals or "bins" into which the various events can be sorted—all the 1-mm events together in one bin, all the 2-mm events in another, and so on. Because everything is measured to the nearest millimeter, each bin actually represents a range; for example, all tracks with a projected length measured as 6 mm in the pictures fall into the bin 5.5-6.5 mm. After all the tracks have been measured, you should count the number of tracks which fall in each bin. We use the symbol ΔN_i to represent the number of tracks falling into the i^{th} bin.

Next, use Table L2 to convert track length into time, so that the time of flight at the beginning and the end of each bin can be

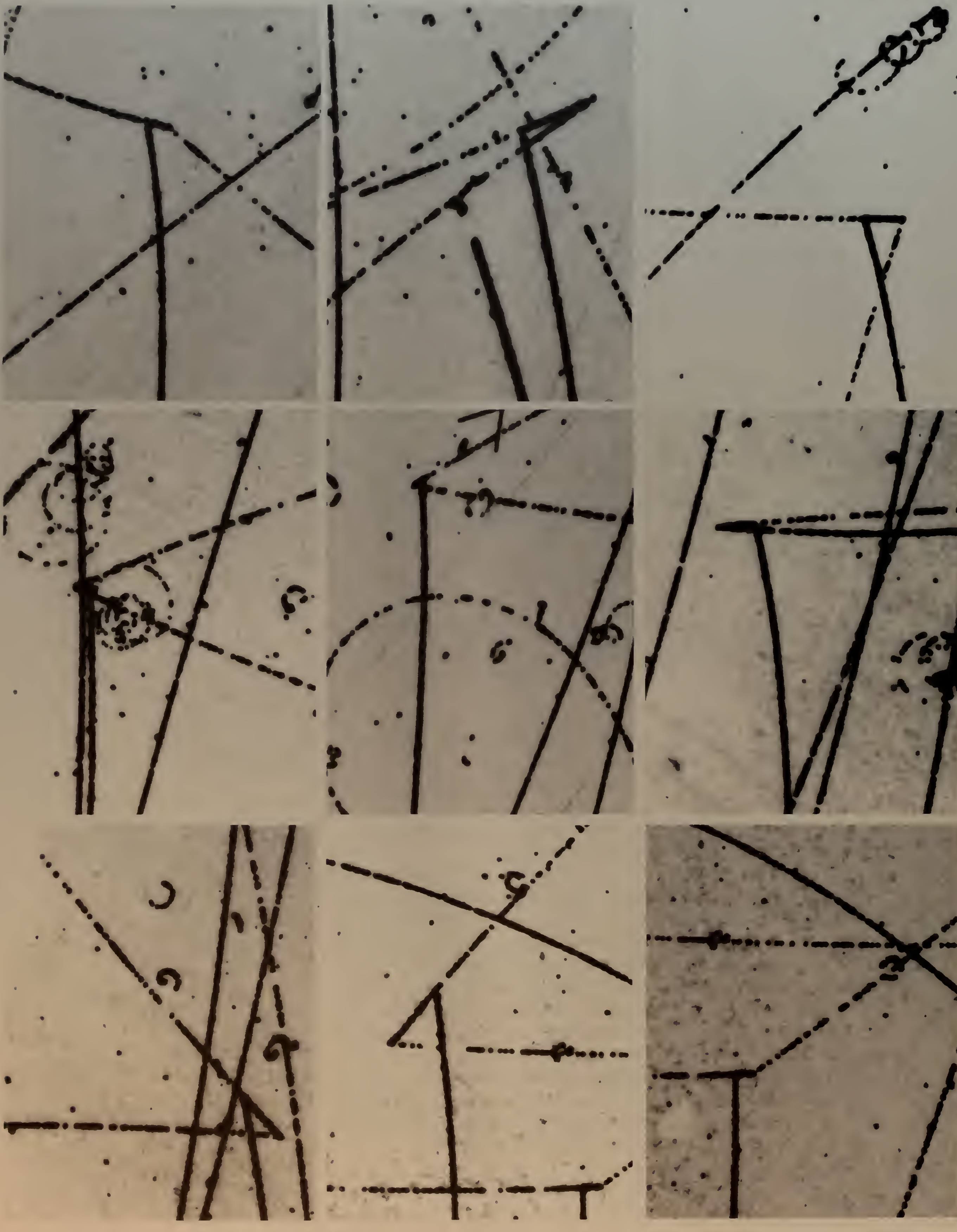


Fig. L 8 Sigma minus decay events (twice actual size).

determined, as well as the time duration of the bin, designated by Δt_i. Thus for example, those tracks with projected length of 6 mm fall in the time bin 0.85×10^{-10} to 1.02×10^{-10} sec, a bin which has a duration $\Delta t = 0.17 \times 10^{-10}$ sec.

2. From the data organized in this way, construct a graph showing N_i, the total number of Σ^- particles remaining undecayed at t_i, the beginning of each bin, versus time. Does your graph have the general shape that you expect?

3. To calculate the decay constant, recall from above that it is defined as the fraction of the observed particles which decay per unit time. Thus for the i^{th} bin $\lambda_i = \Delta N_i / N_i \Delta t_i$. Calculate λ_i for each bin corresponding to a length in the picture of at least 2 mm, but not more than 13 mm. Bins corresponding to shorter lengths are not used because it is not possible to find all the Σ^- tracks with any assurance if they are too short. Bins corresponding to longer track lengths are also omitted from the calculation because the sigmas have nearly come to rest and are likely to be lost by reacting with a proton before they get a chance to decay.

4. Your experimental value of the decay constant λ will be the average of the λ_i. Notice the way the λ_i fluctuate about this average: some of the values of λ_i may even be zero! How do you explain this? (See Background section of this experiment).

5. Calculate your value of the lifetime $\tau = 1/\lambda$ and compare it with the accepted value from the Table of Particles.

6. A detailed mathematical analysis shows that the precision of such a measurement of lifetime is approximately equal to $\tau/\sqrt{n}$ where n is the total number of decays actually used in calculating the λ_i. Therefore, what precision should you quote with your lifetime? Do you agree with the accepted value within the precision of your experiment?

7. If you wish to make a further comparison with theory, you may use your values of λ and N_o (the number of particles present at $t = 0$) in the theoretical equation

$$N = N_0 e^{-\lambda t}$$

which is the radioactive decay law. Plot the theoretical decay curve on the same graph that you constructed in step 2 above. Notice that your first bin starts at $t = 0.23 \times 10^{-10}$ sec, not at 0, so you must first calculate N_o from the number of particles remaining at that time. How do your experimental results agree with the radioactive decay law? How do you account for any deviations?

Q1 For electrons with energies of 200 MeV, 1 GeV, and 20 GeV calculate the radius of curvature of the track in a magnetic field of 1.5 weber/square meter.

Q2 Calculate the kinetic energy of a proton for momenta of 200 MeV/c, 1 GeV/c, and 200 GeV/c.

Q3 Calculate the radius of curvature of the track in a magnetic field of 1.5 weber/square meter for the protons of Problem 2.

Q4 What is the velocity of each of the following particles if its momentum is 1 GeV/c: electron, muon, proton, omega-minus?

BIBLIOGRAPHY AND OTHER RESOURCES

Books on Elementary Particles

The World of Elementary Particles. K. W. Ford (Blaisdell Publishing Co., New York, 1963). A very readable book, especially good in presenting the historical and philosophical background of the new ideas concerning particles. Practically no mathematics is used.

Elementary Particles D. H. Frisch and A. M. Thorndike. (D. Van Nostrand Co. Inc., Princeton, New Jersey, 1963). In the Momentum Series established by the Commission on College Physics. There is a chapter on particle detection techniques. Occasional use is made of the mathematics of a college physics course, but these sections can easily be skipped if desired.

Tracking Down Particles R. D. Hill, (W. A. Benjamin, Inc., New York, 1963). There is practically no mathematics in this account of the particles, the accelerators, and the ideas of modern physics.

Elementary Particles C. N. Yang, (Princeton University Press, Princeton, New Jersey, 1962). Based on the Lectures which Professor Yang gave in 1959. A large amount of information about particles is provided. Relates particle physics to history and other humanities.

Introduction to the Detection of Nuclear Particles in a Bubble Chamber Lawrence Radiation Laboratory. (Ealing Press, Cambridge, Mass. 1964.) Contains some of the pictures used in this unit and some more, with descriptions and background material. Slides and three-dimensional viewer are also available. (See note on page 25.)

Particle Physics, The High-Energy Frontier, M. Stanley Livingston (McGraw Hill, 1968). An introductory survey suitable for a student with a good background in physics. It would also be of interest to teachers who would like a reasonably comprehensive survey which is not filled with mathematical derivations.

Books of General Interest

Contemporary Physics David Park (Harcourt, Brace & World, 1964) Covers several areas of Modern Physics for the general reader. Chapters 6 and 7 deal with elementary particles and high energy physics.

The World of the Atom Henry A. Boorse and Lloyd Motz ed. (Basic Books, New York, 1966) 2 volumes. A source for those who wish to dig deeper into particle physics (or for that matter, atomic or nuclear physics). Contains reprints of papers by leading physicists illuminating the entire history of these fields. In addition to the original papers, there are biographical sketches of many leading physicists as well as general connective discussions by the editors.

Cosmic Rays Bruno Rossi (McGraw-Hill, New York, 1964) An excellent and interesting book suitable for the general reader or the high school physics student.

Book on Experimental Equipment

Accelerators, Machines of Nuclear Physics R. R. Wilson & R. Littauer, (Anchor Books, Doubleday & Company, Garden City, New York, 1960) A popular account in the Science Study Series.

The following items from the Project Physics Reader 6 are especially relevant to particle physics.

Antiprotons, O. Chamberlain et al
The Tracks of Nuclear Particles, Herman Yagoda
CERN, Jeremy Bernstein
Mr. Tompkins Tastes a Japanese Meal, George Gamow
Conservation Laws, Kenneth W. Ford
The Fall of Parity, Martin Gardner
Can Time Go Backwards, Martin Gardner

Films

People and Particles (Project Physics) B & W 28 minutes. A documentary film showing a group of scientists at work testing the laws governing electrons and positrons at high energies. A Project Physics *Film Guide* discusses the main themes of the film and outlines the scheme of the experiment.

The Ultimate Speed (PSSC) B & W 38 minutes. A film of experiments demonstrating that electrons are subject to a limiting speed equal to that of light.

Positron-Electron Annihilation (PSSC) B & W 28 minutes. The conservation of energy with the transformation of matter into radiation is demonstrated in this film of the annihilation of positron-electron pairs.

Synchrotron (An introduction to the design and operation of the Cambridge Electron Accelerator). 16mm, color, sound, 15 minutes (Project Physics)

The World of Enrico Fermi, a documentary montage biography, 16mm, black and white, sound, available as a single film of 48 min. or in two parts about 25 min. each. (Project Physics)

Film Loops. The following Project Physics film loops relate to the physics of elementary particles.

In *Unit 3.* Loops 18, 19. One-dimensional Collisions I and II; 21, 11. Two-dimensional collisions I and II. These four film loops show elastic collisions in slow motion.

In *Unit 5.* Loop 46 Rutherford Scattering. A computer-animated film, in which projectiles are fired toward a nucleus which exerts an inverse-square force.

Transparencies. The following Project Physics transparencies illustrate ideas of importance in the physics of elementary particles.

In *Unit 3.* T19 One-dimensional collisions; T20 Equal mass two-dimensional collisions.

In *Unit 4.* T32 Magnetic fields and moving charges.

In *Unit 6.* T40 Separation of rays; T45 Mass spectrometer.

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